Wilkinson Microwave Anisotropy Probe

Cosmology: The Study of the Universe

Cosmology is the scientific study of the large scale properties of the universe as a whole. It endeavors to use the scientific method to understand the origin, evolution and ultimate fate of the entire Universe. Like any field of science, cosmology involves the formation of theories or hypotheses about the universe which make specific predictions for phenomena that can be tested with observations. Depending on the outcome of the observations, the theories will need to be abandoned, revised or extended to accommodate the data. The prevailing theory about the origin and evolution of our Universe is the so-called Big Bang theory.

This primer in cosmological concepts is organized as follows:

- The main concepts of the Big Bang theory are introduced in the first section with scant regard to actual observations.
- The second section discusses the classic tests of the Big Bang theory that make it so compelling as the likely valid description of our universe.
- The third section discusses observations that highlight limitations of the Big Bang theory and point to a more detailed model of cosmology than the Big Bang theory alone provides. As discussed in the first section, the Big Bang theory predicts a range of possibilities for the structure and evolution of the universe.
- The final section discusses what constraints we can place on the nature of *our* universe based on current data, and indicates how WMAP furthers our understanding of cosmology.
- In addition, a few related topics are discussed based on commmonly asked questions.

If you have a question about cosmology that you don't see answered here or on our FAQ page, please feel free to contact us directly.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 06-03-2011

Wilkinson Microwave Anisotropy Probe

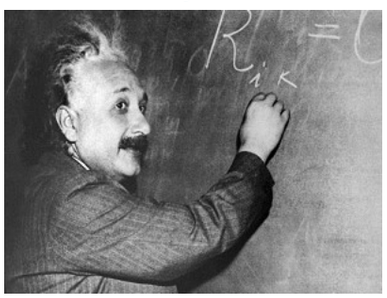
Big Bang Cosmology

The Big Bang Model is a broadly accepted theory for the origin and evolution of our universe. It postulates that 12 to 14 billion years ago, the portion of the universe we can see today was only a few millimeters across. It has since expanded from this hot dense state into the vast and much cooler cosmos we currently inhabit. We can see remnants of this hot dense matter as the now very cold cosmic microwave background radiation which still pervades the universe and is visible to microwave detectors as a uniform glow across the entire sky.

FOUNDATIONS OF THE BIG BANG MODEL

The Big Bang Model rests on two theoretical pillars:

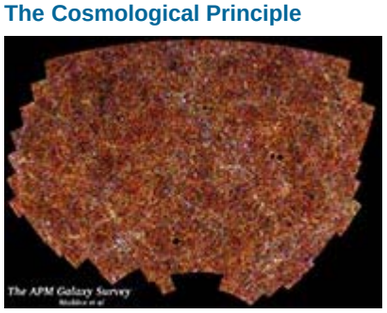
General Relativity



Albert Einstien at the Chalkboard-
source unknown

The first key idea dates to 1916 when Einstein developed his General Theory of Relativity which he proposed as a new theory of gravity. His theory generalizes Isaac Newton's original theory of gravity, c. 1680, in that it is supposed to be valid for bodies in motion as well as bodies at rest. Newton's gravity is only valid for bodies at rest or moving very slowly compared to the speed of light (usually not too restrictive an assumption!). A key concept of General Relativity is that gravity is no longer described by a gravitational "field" but rather it is supposed to be a distortion of space and time itself. Physicist John Wheeler put it well when he said "Matter tells space how to curve, and space tells matter how to move." Originally, the theory was able to account for peculiarities in the orbit of Mercury and the bending of light by the Sun, both unexplained in Isaac Newton's theory of gravity. In recent years, the theory has passed a series of rigorous tests.

The Cosmological Principle



APM Galaxy Survey

After the introduction of General Relativity a number of scientists, including Einstein, tried to apply the new gravitational dynamics to the universe as a whole. At the time this required an assumption about how the matter in the universe was distributed. The simplest assumption to make is that if you viewed the contents of the universe with sufficiently poor vision, it would appear roughly the same everywhere and in every direction. That is, the matter in the universe is homogeneous and isotropic when averaged over very large scales. This is called the Cosmological Principle. This assumption is being tested continuously as we actually observe the distribution of galaxies on ever larger scales. The accompanying picture shows how uniform the distribution of measured galaxies is over a 70° swath of the sky. In addition the cosmic microwave background radiation, the remnant heat from the Big Bang, has a temperature which is highly uniform over the entire sky. This fact strongly supports the notion that the gas which emitted this radiation long ago was very uniformly distributed.

These two ideas form the entire theoretical basis for Big Bang cosmology and lead to very specific predictions for observable properties of the universe. An overview of the Big Bang Model is presented in a set of companion pages.

FURTHER READING

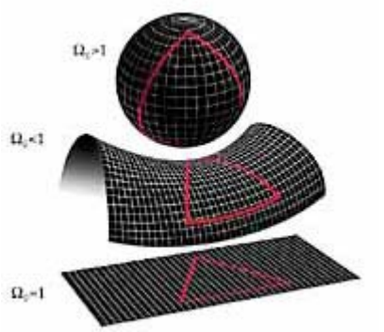
- Peebles, P.J.E., Schramm, D.N., Turner, E.L. & R.G. Kron 1991, "The Case for the Relativistic Hot Big Bang Cosmology", Nature, 352, 769 - 776.
- Peebles, P.J.E., Schramm, D.N., Turner, E.L. & R.G. Kron 1994, "The Evolution of the Universe", Scientific American, 271, 29 - 33.
- Will, Clifford, "Was Einstein Right?"

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Monday, 01-03-2011

Wilkinson Microwave Anisotropy Probe

Foundations of Big Bang Cosmology

The Big Bang model of cosmology rests on two key ideas that date back to the early 20th century: General Relativity and the Cosmological Principle. By assuming that the matter in the universe is distributed uniformly on the largest scales, one can use General Relativity to compute the corresponding gravitational effects of that matter. Since gravity is a property of space-time in General Relativity, this is equivalent to computing the dynamics of space-time itself. The story unfolds as follows:

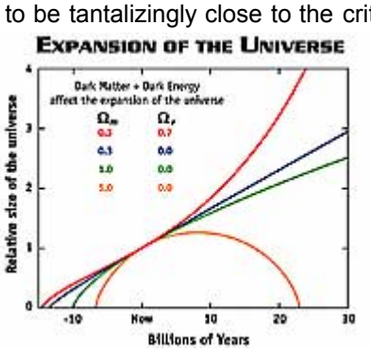


Given the assumption that the matter in the universe is homogeneous and isotropic (The Cosmological Principle) it can be shown that the corresponding distortion of space-time (due to the gravitational effects of this matter) can only have one of three forms, as shown schematically in the picture at left. It can be "positively" curved like the surface of a ball and finite in extent; it can be "negatively" curved like a saddle and infinite in extent; or it can be "flat" and infinite in extent - our "ordinary" conception of space. A key limitation of the picture shown here is that we can only portray the curvature of a 2-dimensional plane of an actual 3-dimensional space! Note that in a closed universe you could start a journey off in one direction and, if allowed enough time, ultimately return to your starting point; in an infinite universe, you would never return.

Before we discuss which of these three pictures describe our universe (if any) we must make a few disclaimers:

- Because the universe has a finite age (~13.7 billion years) we can only see a finite distance out into space: ~13.7 billion light years. This is our so-called horizon. The Big Bang Model does not attempt to describe that region of space significantly beyond our horizon - space-time could well be quite different out there.
- It is possible that the universe has a more complicated global topology than that which is portrayed here, while still having the same local curvature. For example it could have the shape of a torus (doughnut). There may be some ways to test this idea, but most of the following discussion is unaffected.

Matter plays a central role in cosmology. It turns out that the average density of matter uniquely determines the geometry of the universe (up to the limitations noted above). If the density of matter is less than the so-called critical density, the universe is open and infinite. If the density is greater than the critical density the universe is closed and finite. If the density just equals the critical density, the universe is flat, but still presumably infinite. The value of the critical density is very small: it corresponds to roughly 6 hydrogen atoms per cubic meter, an astonishingly good vacuum by terrestrial standards! One of the key scientific questions in cosmology today is: what is the average density of matter in our universe? While the answer is not yet known for certain, it appears to be tantalizingly close to the critical density.



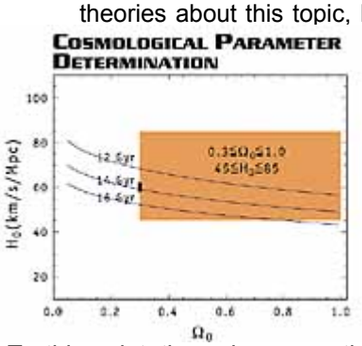
Given a law of gravity and an assumption about how the matter is distributed, the next step is to work out the dynamics of the universe - how space and the matter in it evolves with time. The details depend on some further information about the matter in the universe, namely its density (mass per unit volume) and its pressure (force it exerts per unit area),

but the generic picture that emerges is that the universe started from a very small volume, an event later dubbed the Big Bang, with an initial expansion rate. For the most part this *rate* of expansion has been slowing down (decelerating) ever since due to the gravitational pull of the matter on itself. A key question for the fate of the universe is whether or not the pull of gravity is strong enough to ultimately reverse the expansion and cause the universe to collapse back on itself. In fact, recent observations have raised the possibility that the expansion of the universe might in fact be speeding up (accelerating), raising the possibility that the evolution of the universe is now dominated by a bizarre form of matter which has a negative pressure.

The picture above shows a number of possible scenarios for the relative size of the universe vs. time: the bottom (green) curve represents a flat, critical density universe in which the expansion rate is continually slowing down (the curves becomes ever more horizontal). The middle (blue) curve shows an open, low density universe whose expansion is also slowing down, but not as much as the critical density universe because the pull of gravity is not as strong. The top (red) curve shows a universe in which a large fraction of its mass/energy maybe in the very vacuum of space itself, known as the "cosmological constant", a leading candidate for the so-called "dark energy" which is causing the expansion of the universe to speed up (accelerate). There is growing evidence that our universe is following the red curve.

Please keep in mind the following important points to avoid misconceptions about the Big Bang and expansion:

- The Big Bang did not occur at a single point in space as an "explosion." It is better thought of as the simultaneous appearance of space everywhere in the universe. That region of space that is within our present horizon was indeed no bigger than a point in the past. Nevertheless, if all of space both inside and outside our horizon is infinite now, it was born infinite. If it is closed and finite, then it was born with zero volume and grew from that. In neither case is there a "center of expansion" - a point from which the universe is expanding away from. In the ball analogy, the radius of the ball grows as the universe expands, but all points on the surface of the ball (the universe) recede from each other in an identical fashion. The interior of the ball should not be regarded as part of the universe in this analogy.
- By definition, the universe encompasses all of space and time as we know it, so it is beyond the realm of the Big Bang model to postulate what the universe is expanding into. In either the open or closed universe, the only "edge" to space-time occurs at the Big Bang (and perhaps its counterpart the Big Crunch), so it is not logically necessary (or sensible) to consider this question.
- It is beyond the realm of the Big Bang Model to say what gave rise to the Big Bang. There are a number of speculative theories about this topic, but none of them make realistically testable predictions as of yet.



To this point, the only assumption we have made about the universe is that its matter is distributed homogeneously and isotropically on large scales. There are a number of free parameters in this family of Big Bang models that must be fixed by observations of our universe. The most important ones are: the geometry of the universe (open, flat or closed); the present expansion rate (the Hubble constant); the overall course of expansion, past and future, which is determined by the fractional density of the different types of matter in the universe. Note that the present age of the universe follows from the expansion history and present expansion rate.

As noted above, the geometry and evolution of the universe are determined by the fractional contribution of various types of matter. Since both energy density and pressure contribute to the strength of gravity in General Relativity, cosmologists classify types of matter by its "equation of state" the relationship between its pressure and energy density. The basic classification scheme is:

- **Radiation**: composed of massless or nearly massless particles that move at the speed of light. Known examples include photons (light) and neutrinos. This form of matter is characterized by having a large positive pressure.
- **Baryonic matter**: this is "ordinary matter" composed primarily of protons, neutrons and electrons. This form of matter has essentially no pressure of cosmological importance.
- **Dark matter**: this generally refers to "exotic" non-baryonic matter that interacts only weakly with ordinary matter. While no such matter has ever been directly observed in the laboratory, its existence has long been suspected for reasons discussed in a subsequent page. This form of matter also has no cosmologically significant pressure.
- **Dark energy**: this is a truly bizarre form of matter, or perhaps a property of the vacuum itself, that is characterized by a large,

negative pressure. This is the only form of matter that can cause the expansion of the universe to accelerate, or speed up.

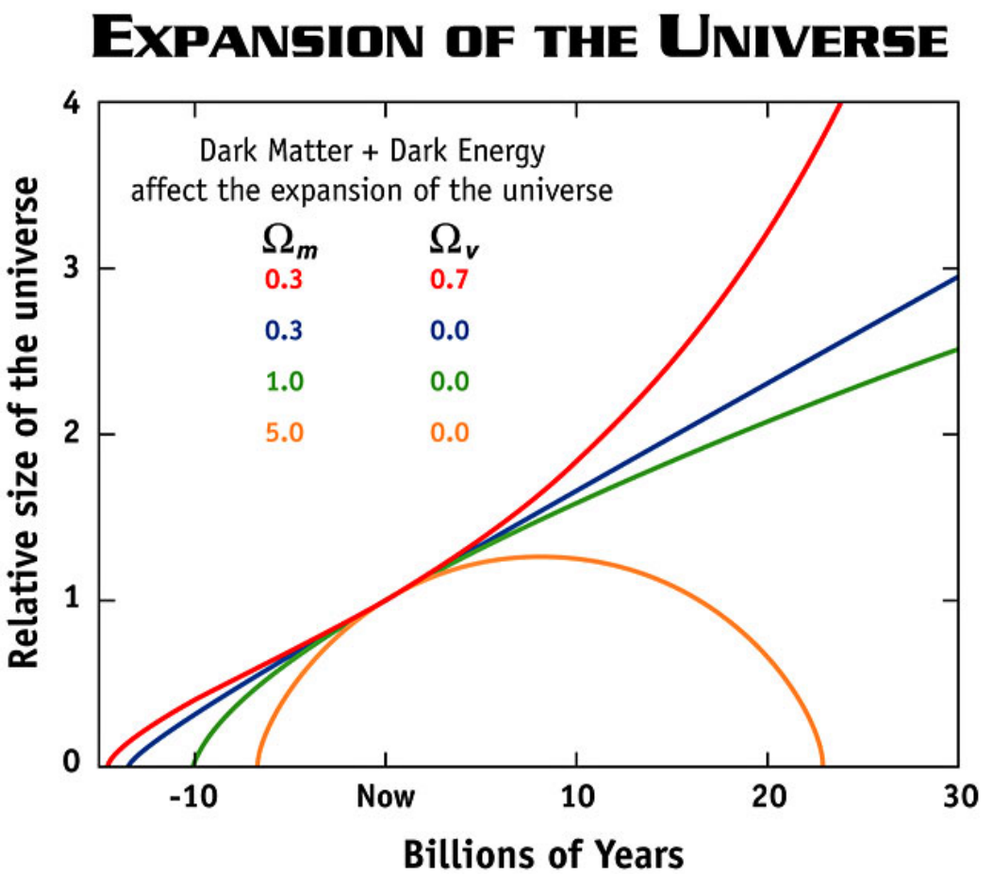
One of the central challenges in cosmology today is to determine the relative and total densities (energy per unit volume) in each of these forms of matter, since this is essential to understanding the evolution and ultimate fate of our universe.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Monday, 05-24-2010

Expansion of the Universe

Long Description (Return to Concepts page)

Possible scenarios for the expansion (and possibly contraction) of the universe: the bottom orange curve represents a closed, high density universe which expands for several billion years, then ultimately turns around and collapses under its own weight. The green curve represents a flat, critical density universe in which the expansion rate continually slows down (the curves becomes ever more horizontal). The blue curve shows an open, low density universe whose expansion is also slowing down, but not as much as the previous two because the pull of gravity is not as strong. The top (red) curve shows a universe in which a large fraction of the matter is in a form dubbed "dark energy" which is causing the expansion of the universe to speed up (accelerate). There is growing evidence that our universe is following the red curve.



wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

Tests of Big Bang Cosmology

The Big Bang Model is supported by a number of important observations, each of which are described in more detail on separate pages:

The expansion of the universe
: Edwin Hubble's 1929 observation that galaxies were generally receding from us provided the first clue that the Big Bang theory might be right.

The abundance of the light elements H, He, Li
: The Big Bang theory predicts that these light elements should have been fused from protons and neutrons in the first few minutes after the Big Bang.

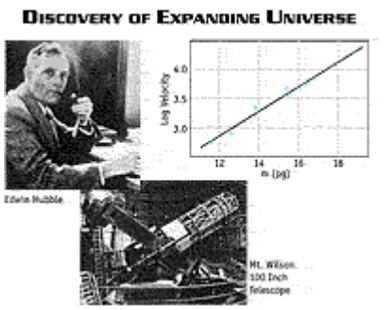
The cosmic microwave background (CMB) radiation
: The early universe should have been very hot. The cosmic microwave background radiation is the remnant heat leftover from the Big Bang.

These three measurable signatures strongly support the notion that the universe evolved from a dense, nearly featureless hot gas, just as the Big Bang model predicts.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

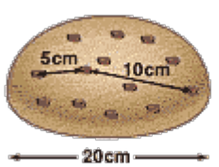
Tests of Big Bang: Expansion

Edwin Hubble



The Big Bang model was a natural outcome of Einstein's General Relativity as applied to a homogeneous universe. However, in 1917, the idea that the universe was expanding was thought to be absurd. So Einstein invented the cosmological constant as a term in his General Relativity theory that allowed for a static universe. In 1929, Edwin Hubble announced that his observations of galaxies outside our own Milky Way showed that they were systematically moving away from us with a speed that was proportional to their distance from us. The more distant the galaxy, the faster it was receding from us. The universe was expanding after all, just as General Relativity originally predicted! Hubble observed that the light from a given galaxy was shifted further toward the red end of the light spectrum the further that galaxy was from our galaxy.

The Hubble Constant



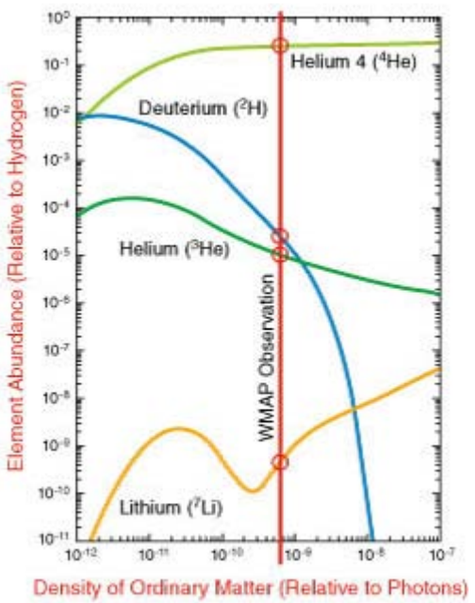
The specific form of Hubble's expansion law is important: the speed of recession is proportional to distance. The expanding raisin bread model at left illustrates why this is important. If every portion of the bread expands by the same amount in a given interval of time, then the raisins would recede from each other with exactly a Hubble type expansion law. In a given time interval, a nearby raisin would move relatively little, but a distant raisin would move relatively farther - and the same behavior would be seen from any raisin in the loaf. In other words, the Hubble law is just what one would expect for a *homogeneous* expanding universe, as predicted by the Big Bang theory. Moreover no raisin, or galaxy, occupies a special place in this universe - unless you get too close to the edge of the loaf where the analogy breaks down.

The current WMAP results show the Hubble Constant to be 71.0 ± 2.5 (km/sec)/Mpc. If the WMAP data is combined with other cosmological data, the best estimate is 70.4 ± 1.4 (km/sec)/Mpc.

Tests of Big Bang: The Light Elements

NUCLEOSYNTHESIS IN THE EARLY UNIVERSE

The term nucleosynthesis refers to the formation of heavier elements, atomic nuclei with many protons and neutrons, from the fusion of lighter elements. The Big Bang theory predicts that the early universe was a very hot place. One second after the Big Bang, the temperature of the universe was roughly 10 billion degrees and was filled with a sea of neutrons, protons, electrons, anti-electrons (positrons), photons and neutrinos. As the universe cooled, the neutrons either decayed into protons and electrons or combined with protons to make deuterium (an isotope of hydrogen). During the first three minutes of the universe, most of the deuterium combined to make helium. Trace amounts of lithium were also produced at this time. This process of light element formation in the early universe is called “Big Bang nucleosynthesis” (BBN).



The predicted abundance of deuterium, helium and lithium depends on the density of ordinary matter in the early universe, as shown in the figure at left. These results indicate that the yield of helium is relatively insensitive to the abundance of ordinary matter, above a certain threshold. We generically expect about 24% of the ordinary matter in the universe to be helium produced in the Big Bang. This is in very good agreement with observations and is another major triumph for the Big Bang theory.

However, the Big Bang model can be tested further. Given a precise measurement of the abundance of ordinary matter, the predicted abundances of the other light elements becomes highly constrained. The WMAP satellite is able to directly measure the ordinary matter density and finds a value of 4.6% (±0.2%), indicated by the vertical red line in the graph. This leads to predicted abundances shown by the circles in the graph, which are in good agreement with observed abundances. This is an important and detailed test of nucleosynthesis and is further evidence in support of the Big Bang theory. Had the results been in conflict, it would point to 1) errors in the data, 2) an incomplete understanding of the process of Big Bang nucleosynthesis, 3) a misunderstanding of the mechanisms that produce fluctuations in the microwave background radiation, or 4) a more fundamental problem with the Big Bang theory.

NUCLEOSYNTHESIS IN STARS

Elements heavier than lithium are all synthesized in stars. During the late stages of stellar evolution, massive stars burn helium to carbon, oxygen, silicon, sulfur, and iron. Elements heavier than iron are produced in two ways: in the outer envelopes of super-giant stars and in the explosion of a supernovae. All carbon-based life on Earth is literally composed of stardust.

SOME HISTORY

In 1948, Physicist George Gamow hypothesized that all of the elements might have been made in the hot and dense early universe. He suggested to his student, Ralph Alpher, that he calculate this. Alpher did so for his PhD thesis, with Robert Herman participating in much of the work. Alpher and Herman found that Gamow was wrong: most elements could not have been made in the early universe. The problem is with neutron capture. Neutrons decay in about 10 minutes, and their density decreases as the universe expands in that time. There just isn't enough time to keep building up to the heavier elements before the neutrons are gone. The heavy elements are made later, in stars. Only the lightest elements are built up in the early universe. The important prediction that the cosmic microwave background (CMB) exists, and has a blackbody spectrum with a temperature of about 5 degrees above absolute zero, was a by-product of this work.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

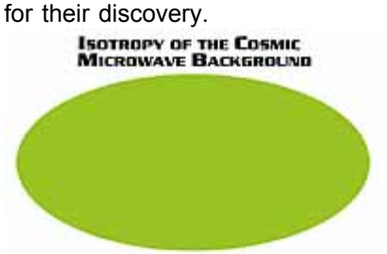
Wilkinson Microwave Anisotropy Probe

Tests of Big Bang: The CMB

The Big Bang theory predicts that the early universe was a very hot place and that as it expands, the gas within it cools. Thus the universe should be filled with radiation that is literally the remnant heat left over from the Big Bang, called the “cosmic microwave background radiation”, or CMB.

DISCOVERY OF THE COSMIC MICROWAVE BACKGROUND

The existence of the CMB radiation was first predicted by Ralph Alpher, Robert Herman, and George Gamow in 1948, as part of their work on Big Bang Nucleosynthesis. It was first observed inadvertently in 1965 by Arno Penzias and Robert Wilson at the Bell Telephone Laboratories in Murray Hill, New Jersey. The radiation was acting as a source of excess noise in a radio receiver they were building. Coincidentally, researchers at nearby Princeton University, led by Robert Dicke and including Dave Wilkinson of the WMAP science team, were devising an experiment to find the CMB. When they heard about the Bell Labs result they immediately realized that the CMB had been found. The result was a pair of papers in the Astrophysical Journal (vol. 142 of 1965): one by Penzias and Wilson detailing the observations, and one by Dicke, Peebles, Roll, and Wilkinson giving the cosmological interpretation. Penzias and Wilson shared the 1978 Nobel prize in physics for their discovery.



Today, the CMB radiation is very cold, only 2.725° above absolute zero, thus this radiation shines primarily in the microwave portion of the electromagnetic spectrum, and is invisible to the naked eye. However, it fills the universe and can be detected everywhere we look. In fact, if we could see microwaves, the entire sky would glow with a brightness that was astonishingly uniform in every direction. The picture at left shows a false color depiction of the temperature (brightness) of the CMB over the full sky (projected onto an oval, similar to a map of the Earth). The temperature is uniform to better than one part in a thousand! This uniformity is one compelling reason to interpret the radiation as remnant heat from the Big Bang; it would be very difficult to imagine a local source of radiation that was this uniform. In fact, many scientists have tried to devise alternative explanations for the source of this radiation but none have succeeded.

WHY STUDY THE COSMIC MICROWAVE BACKGROUND?

Since light travels at a finite speed, astronomers observing distant objects are looking into the past. Most of the stars that are visible to the naked eye in the night sky are 10 to 100 light years away. Thus, we see them as they were 10 to 100 years ago. We observe Andromeda, the nearest big galaxy, as it was about 2.5 million years ago. Astronomers observing distant galaxies with the Hubble Space Telescope can see them as they were only a few billion years after the Big Bang. (Most cosmologists believe that the universe is between 12 and 14 billion years old.)

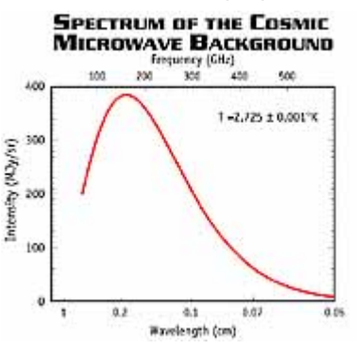
The CMB radiation was emitted only a few hundred thousand years after the Big Bang, long before stars or galaxies ever existed. Thus, by studying the detailed physical properties of the radiation, we can learn about conditions in the universe on

very large scales, since the radiation we see today has traveled over such a large distance, and at very early times.

THE ORIGIN OF THE COSMIC MICROWAVE BACKGROUND

One of the profound observations of the 20th century is that the universe is expanding. This expansion implies the universe was smaller, denser and hotter in the distant past. When the visible universe was half its present size, the density of matter was eight times higher and the cosmic microwave background was twice as hot. When the visible universe was one hundredth of its present size, the cosmic microwave background was a hundred times hotter (273 degrees above absolute zero or 32 degrees Fahrenheit, the temperature at which water freezes to form ice on the Earth's surface). In addition to this cosmic microwave background radiation, the early universe was filled with hot hydrogen gas with a density of about 1000 atoms per cubic centimeter. When the visible universe was only one hundred millionth its present size, its temperature was 273 million degrees above absolute zero and the density of matter was comparable to the density of air at the Earth's surface. At these high temperatures, the hydrogen was completely ionized into free protons and electrons.

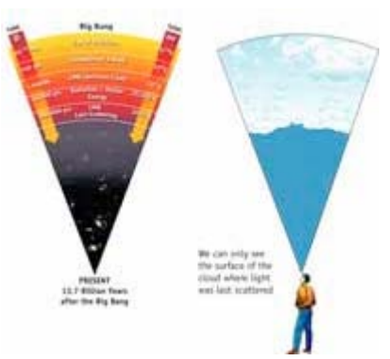
Since the universe was so very hot through most of its early history, there were no atoms in the early universe, only free electrons and nuclei. (Nuclei are made of neutrons and protons). The cosmic microwave background photons easily scatter off of electrons. Thus, photons wandered through the early universe, just as optical light wanders through a dense fog. This process of multiple scattering produces what is called a “thermal” or “blackbody” spectrum of photons. According to the Big Bang theory, the frequency spectrum of the CMB should have this blackbody form. This was indeed measured with tremendous accuracy by the FIRAS experiment on NASA's COBE satellite.



This figure shows the prediction of the Big Bang theory for the energy spectrum of the cosmic microwave background radiation compared to the observed energy spectrum. The FIRAS experiment measured the spectrum at 34 equally spaced points along the blackbody curve. The error bars on the data points are so small that they can not be seen under the predicted curve in the figure! There is no alternative theory yet proposed that predicts this energy spectrum. The accurate measurement of its shape was another important test of the Big Bang theory.

“SURFACE OF LAST SCATTERING”

Eventually, the universe cooled sufficiently that protons and electrons could combine to form neutral hydrogen. This was thought to occur roughly 400,000 years after the Big Bang when the universe was about one eleven hundredth its present size. Cosmic microwave background photons interact very weakly with neutral hydrogen.



The behavior of CMB photons moving through the early universe is analogous to the propagation of optical light through the Earth's atmosphere. Water droplets in a cloud are very effective at scattering light, while optical light moves freely through clear air. Thus, on a cloudy day, we can look through the air out towards the clouds, but can not see through the opaque clouds. Cosmologists studying the cosmic microwave background radiation can look through much of the universe back to when it was opaque: a view back to 400,000 years after the Big Bang. This “wall of light“ is called the

surface of last scattering since it was the last time most of the CMB photons directly scattered off of matter. When we make maps of the temperature of the CMB, we are mapping this surface of last scattering.

As shown above, one of the most striking features about the cosmic microwave background is its uniformity. Only with very sensitive instruments, such as COBE and WMAP, can cosmologists detect fluctuations in the cosmic microwave background temperature. By studying these fluctuations, cosmologists can learn about the origin of galaxies and large scale structures of galaxies and they can measure the basic parameters of the Big Bang theory.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Tuesday, 05-25-2010

Wilkinson Microwave Anisotropy Probe

Beyond Big Bang Cosmology

The Big Bang model is not complete. For example, it does not explain *why* the universe is so uniform on the very largest scales or, indeed, why it is so *non*-uniform on smaller scales, i.e., how stars and galaxies came to be.

The Big Bang model is based on the Cosmological Principle which assumes that matter in the universe is uniformly distributed on all scales - large and small. This is a very useful approximation that allows one to develop the basic Big Bang scenario, but a more complete understanding of our universe requires going beyond the Cosmological Principle. Many cosmologists suspect that inflation theory, an extension of the Big Bang theory, may provide the framework for explaining the large-scale uniformity of our universe and the origin of structure within it.

The first two pages below provide an overview of the origin and growth of structure in our universe. The last page presents an overview of the inflationary universe model and explains how inflation answers the some of the puzzles of the standard Big Bang model.

Structure in the universe
: The Big Bang theory makes no attempt to explain how structures like stars and galaxies came to exist in the universe.

Fluctuations in the cosmic microwave background (CMB) radiation
: The temperature of the CMB is observed to vary slightly across the sky. What produced these fluctuations and how do they relate to stars and galaxies?

The inflationary universe
: A very short, but especially rapid burst of growth in the *very* early universe (“inflation”) provides an elegant, yet untested, explanation of the above puzzles.

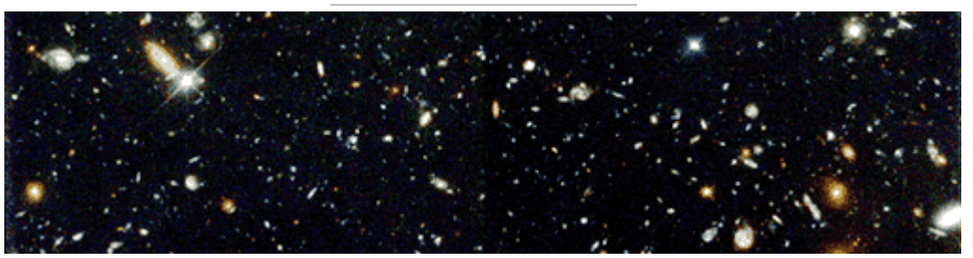
wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

How Did Structure Form in the Universe?

Astronomers observe considerable structure in the universe, from stars to galaxies to clusters and superclusters of galaxies. The famous "Deep Field Image" taken by the Hubble Space Telescope, shown below, provides a stunning view of such structure. How did these structures form? The Big Bang theory is widely considered to be a successful theory of cosmology, but the theory is incomplete. It does not account for the needed fluctuations to produce the structure we see. Most cosmologists believe that the galaxies that we observe today grew from the gravitational pull of small fluctuations in the nearly-uniform density of the early universe. These fluctuations leave an imprint in the cosmic microwave background radiation in the form of temperature fluctuations from point to point across the sky. The WMAP satellite measures these small fluctuations in the temperature of the cosmic microwave background radiation and in turn probe the early stages of structure formation.

Hubble Deep Field Image:



HST press release describing this image

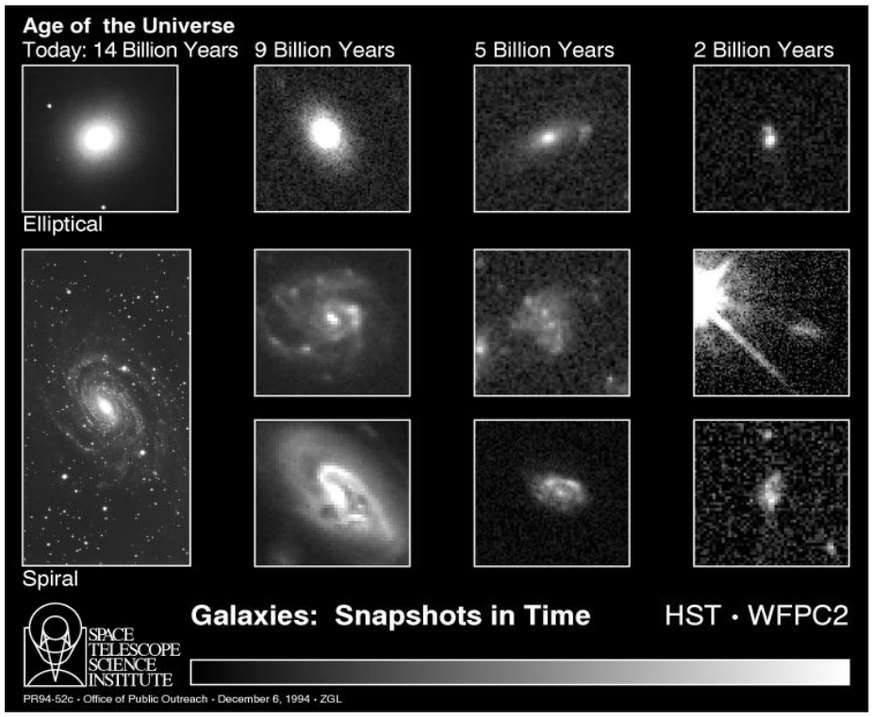
In its simplest form, the Big Bang theory assumes that matter and radiation are uniformly distributed throughout the universe and that general relativity is universally valid. While this can account for the existence of the cosmic microwave background radiation and explain the origin of the light elements, it does not explain the existence of galaxies and large-scale structure. The solution of the structure problem must be built into the framework of the Big Bang theory.

GRAVITATIONAL FORMATION OF STRUCTURE

Most cosmologists believe that the galaxies that we observe today grew gravitationally out of small fluctuations in the density of the universe through the following sequence of events:

- When the universe was one thousandth its present size (roughly 500,000 years after the Big Bang), the density of matter in the region of space that now contains the Milky Way, our home galaxy, was perhaps 0.5% higher than in adjacent regions. Because its density was higher, this region of space expanded more slowly than surrounding regions.
- As a result of this slower expansion, its relative over-density grew. When the universe was one hundredth its present size (roughly 15 million years after the Big Bang), our region of space was probably 5% denser than the surrounding regions.
- This gradual growth continued as the universe expanded. When the universe was one fifth its present size (roughly 1.2 billion years after the Big Bang), our region of space was probably twice as dense as neighboring regions. Cosmologists speculate that the inner portions of our Galaxy (and similar galaxies) were assembled at this time. The stars in the outer regions of our Galaxy were probably assembled in the more recent past. Some cosmologists suspect that some of the objects recently detected by the Hubble Space Telescope may be galaxies in formation.

HST Images of Galaxies in Formation?



HST press release describing this image

OBSERVING THESE SMALL FLUCTUATIONS

Tiny variations in the density of matter in the early universe leave an imprint in the cosmic microwave background radiation in the form of temperature fluctuations from point to point across the sky. These temperature fluctuations are minute: one part of the sky might have a temperature of 2.7251 Kelvin (degrees above absolute zero), while another part might have a temperature of 2.7249 Kelvin. NASA's Cosmic Background Explorer (COBE) satellite, has detected these tiny fluctuations on large angular scales. WMAP re-measures the fluctuations with both higher angular resolution and sensitivity. The mission summary page offers a quick introduction to how WMAP achieves this sensitivity - more details are available on the technical information page.

WHAT MADE THESE SMALL FLUCTUATIONS?

While gravity can enhance the tiny fluctuations seen in the early universe, it can not produce these fluctuations. Cosmologists speculate about the new physics needed to produce the primordial fluctuations that formed galaxies. Two popular ideas are:

- Inflation
- Topological Defects

These different theories make very different predictions about the properties of the cosmic microwave background fluctuations. For example, the inflationary theory predicts that the largest temperature fluctuations should have an angular scale of one degree, while the defect models predict a smaller characteristic scale. WMAP, with its superb sensitivity, indicates that the inflationary model is more likely.

LEARN MORE ABOUT STRUCTURE FORMATION AT THESE SITES:

The Sloan Digital Sky Survey (SDSS)

This group plans to map the positions of over 100 million galaxies and determine the distances to over a million galaxies and quasars. The effort will produce the largest (known) survey to date of cosmic structure in the universe. You can learn more about the details of the SDSS by visiting their home page at Fermilab.

The Virgo Consortium

The Virgo Consortium is an international grouping of scientists carrying out super computer simulations of the formation of galaxies, galaxy clusters, large-scale structure, and of the evolution of the intergalactic medium. Although most of the consortium members are British, there are important nodes in Canada, the United States, and Germany.

The University of Washington N-Body Shop

This group creates software simulations for studying large-scale structure formation and planet formation, and host an interesting image gallery.

The Hubble Space Telescope

HST has been able to observe distant galaxies and study the formation and evolution of galaxies. A well known image depicting this is a Hubble Deep Field image released on January 15th, 1996.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

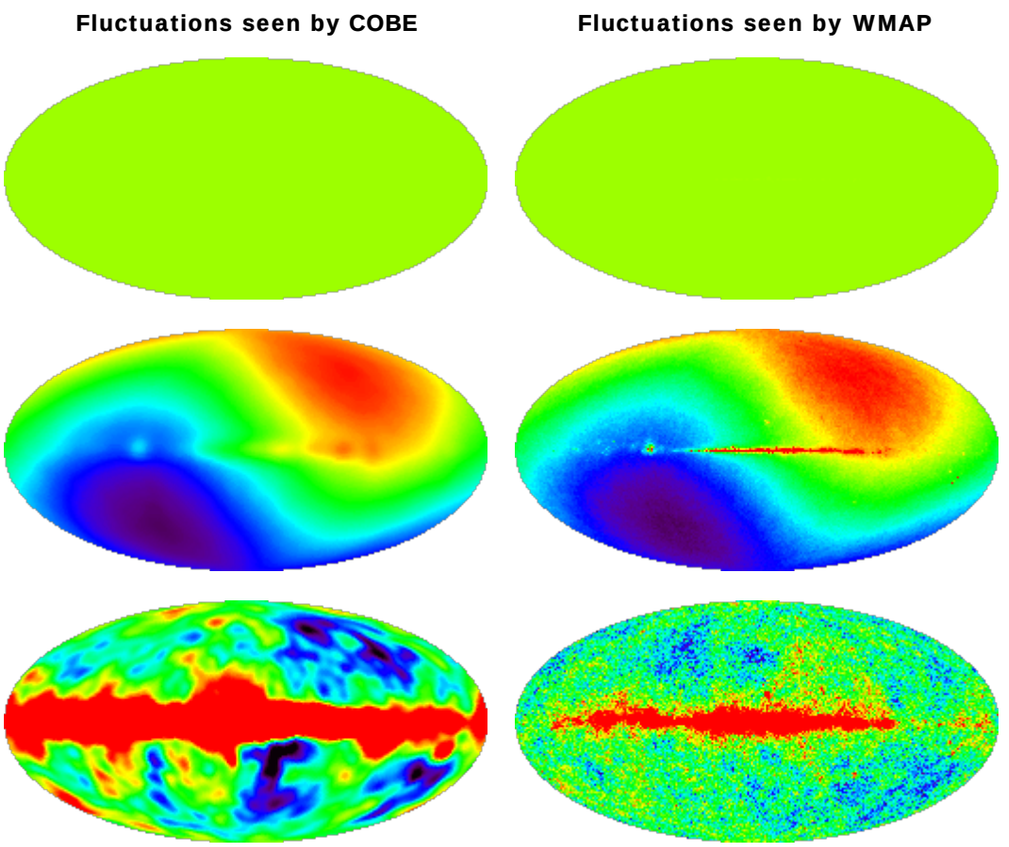
Fluctuations in the Cosmic Microwave Background

The cosmic microwave background is the afterglow radiation left over from the hot Big Bang. Its temperature is extremely uniform all over the sky. However, tiny temperature variations or fluctuations (at the part per million level) can offer great insight into the origin, evolution, and content of the universe.

If you were approaching the Earth on a spaceship, the first thing you would notice is that the planet is spherical. As you drew closer to the Earth, you would see the surface divide into continents and oceans. You would need to study the Earth's surface very carefully to see the mountains, cities, forests and deserts that cover the continents.

Similarly, when cosmologists first looked at the microwave sky, thirty years ago, they noticed it was nearly uniform. As observations improved, they detected the dipole anisotropy. Finally, in 1992, the Cosmic Background Explorer (COBE) satellite made the first detection analogous to seeing "mountains on the surface of the Earth": it detected cosmological fluctuations in the microwave background temperature. Several members of the WMAP science team help lead the COBE program and build the spacecraft. COBE's detection was confirmed by the Far InfraRed Survey (FIRS) balloon-borne experiment.

Comparison of COBE and WMAP sky images



In the comparison of the images above, images on the left produced by the COBE science team, show three false color images of the sky as seen at microwave frequencies. The images on the right show one of our computer simulations of what the WMAP experiment detects. Note that WMAP detects much finer features than are visible in the COBE maps of the sky. This additional angular resolution allows scientists to infer a great deal of additional information, beyond that supplied by COBE, about conditions in the early universe.

The orientation of the maps are such that the plane of the Milky Way runs horizontally across the center of each image. The top pair of figures show the temperature of the microwave sky in a scale in which blue is 0 Kelvin (absolute zero) and red is 4

Kelvin. Note that the temperature appears completely uniform on this scale. The actual temperature of the cosmic microwave background is 2.725 Kelvin. The middle image pair show the same map displayed in a scale such that blue corresponds to 2.721 Kelvin and red is 2.729 Kelvin. The "yin-yang" pattern is the dipole anisotropy that results from the motion of the Sun relative to the rest frame of the cosmic microwave background. The bottom figure pair shows the microwave sky after the dipole anisotropy has been subtracted from the map. This removal eliminates most of the fluctuations in the map: the ones that remain are thirty times smaller. On this map, the hot regions, shown in red, are 0.0002 Kelvin hotter than the cold regions, shown in blue.

There are two main sources for the fluctuations seen in the last figure:

- Emission from the Milky Way dominates the equator of the map but is quite small away from the equator.
- Fluctuating emission from the edge of the visible universe dominates the regions away from the equator.
- There is also residual noise in the maps from the instruments themselves, but this noise is quite small compared to the signals in these maps.

These cosmic microwave temperature fluctuations are believed to trace fluctuations in the density of matter in the early universe, as they were imprinted shortly after the Big Bang. This being the case, they reveal a great deal about the early universe and the origin of galaxies and large scale structure in the universe.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

What is the Inflation Theory?

The Inflation Theory proposes a period of extremely rapid (exponential) expansion of the universe during its first few moments. It was developed around 1980 to explain several puzzles with the standard Big Bang theory, in which the universe expands relatively gradually throughout its history.

LIMITATIONS OF THE BIG BANG THEORY

While the Big Bang theory successfully explains the "blackbody spectrum" of the cosmic microwave background radiation and the origin of the light elements, it has three significant problems:

- The Flatness Problem:
  WMAP has determined the geometry of the universe to be nearly flat. However, under Big Bang cosmology, curvature grows with time. A universe as flat as we see it today would require an extreme fine-tuning of conditions in the past, which would be an unbelievable coincidence.
- The Horizon Problem:
  Distant regions of space in opposite directions of the sky are so far apart that, assuming standard Big Bang expansion, they could never have been in causal contact with each other. This is because the light travel time between them exceeds the age of the universe. Yet the uniformity of the cosmic microwave background temperature tells us that these regions must have been in contact with each other in the past.
- The Monopole Problem:
  Big Bang cosmology predicts that a very large number of heavy, stable "magnetic monopoles" should have been produced in the early universe. However, magnetic monopoles have never been observed, so if they exist at all, they are much more rare than the Big Bang theory predicts.

THE INFLATION THEORY

The Inflation Theory, developed by Alan Guth, Andrei Linde, Paul Steinhardt, and Andy Albrecht, offers solutions to these problems and several other open questions in cosmology. It proposes a period of extremely rapid (exponential) expansion of the universe prior to the more gradual Big Bang expansion, during which time the energy density of the universe was dominated by a cosmological constant-type of vacuum energy that later decayed to produce the matter and radiation that fill the universe today.

Inflation was both rapid, and strong. It increased the linear size of the universe by more than 60 "e-folds", or a factor of ~10^26 in only a small fraction of a second! Inflation is now considered an extension of the Big Bang theory since it explains the above puzzles so well, while retaining the basic paradigm of a homogeneous expanding universe. Moreover, Inflation Theory links important ideas in modern physics, such as symmetry breaking and phase transitions, to cosmology.

HOW DOES INFLATION SOLVE THESE PROBLEMS?

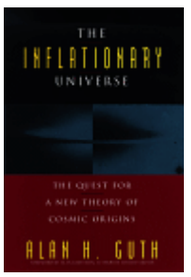
- The Flatness Problem:
  Imagine living on the surface of a soccer ball (a 2-dimensional world). It might be obvious to you that this surface was curved and that you were living in a closed universe. However, if that ball expanded to the size of the Earth, it would appear flat to you, even though it is still a sphere on larger scales. Now imagine increasing the size of that ball to astronomical scales. To you, it would appear to be flat as far as you could see, even though it might have been very curved to start with. Inflation stretches any initial curvature of the 3-dimensional universe to near flatness.
- The Horizon Problem:
  Since Inflation supposes a burst of exponential expansion in the early universe, it follows that distant regions were actually much closer together prior to Inflation than they would have been with only standard Big Bang expansion. Thus, such regions could have been in causal contact prior to Inflation and could have attained a uniform temperature.
- The Monopole Problem:
  Inflation allows for magnetic monopoles to exist as long as they were produced prior to the period of inflation. During inflation, the density of monopoles drops exponentially, so their abundance drops to undetectable levels.

As a bonus, Inflation also explains the origin of structure in the universe. Prior to inflation, the portion of the universe we can observe today was microscopic, and quantum fluctuation in the density of matter on these microscopic scales expanded to astronomical scales during Inflation. Over the next several hundred million years, the higher density regions condensed into

stars, galaxies, and clusters of galaxies.

FURTHER READING:

- Alan H. Guth & Paul J.Steinhardt, "The Inflationary Universe", Scientific American, May 1984.
- Andrei Linde, "The Self-Reproducing Inflationary Universe", Scientific American, November 1994.
- Scott Watson, "An Exposition on Inflationary Cosmology", WWWarticle, 2000.
- Alan H. Guth, "The Inflationary Universe : The Quest for a New Theory of Cosmic Origins", 1998.



wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

Our Universe

So far, we have only described the Big Bang model in general terms: on the largest scales we can observe, the universe appears nearly uniform, it is currently expanding, and there is strong evidence that it was hotter and denser in the past. Now we would like the answers to some more specific questions:

- What types of matter and energy fill the universe? How much of each?
- How rapidly is the universe expanding today?
- How old is the universe today?
- What is the overall shape of the universe? Open, flat, closed, or otherwise?
- How is the expansion changing with time?
- What is the ultimate fate of the universe?

In this section, we address each of these questions in turn by summarizing the observations that inform each of these questions. There are many useful probes of the nature of our universe, each of which constrains one or more particular aspects of the Big Bang model and our understanding of structure formation. Indeed, the coming decade is being dubbed the era of precision cosmology as observations of supernova, galaxies and clusters, the cosmic microwave background radiation and the abundance of light elements each becomes mature. Taken together, these data will strongly constrain the model of our universe and may even point to the need for a radical rethinking of our understanding of cosmology.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

What is the Universe Made Of?

One of the key questions that needs to be answered by astrophysicists is what is really out there? And of what is it all made? Without this understanding it is impossible to come to any firm conclusions about how the universe evolved.

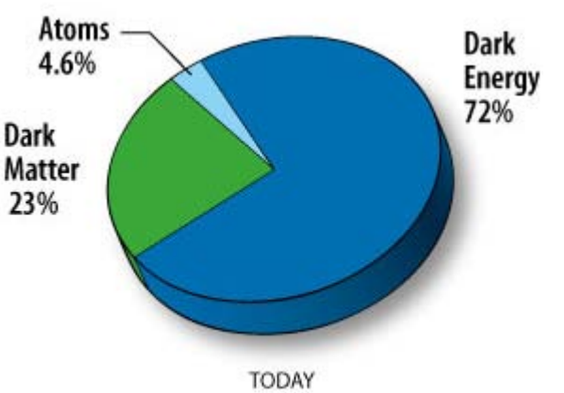
PROTONS, NEUTRONS AND ELECTRONS: THE STUFF OF LIFE

You, this computer, the air we breathe, and the distant stars are all made up of protons, neutrons and electrons. Protons and neutrons are bound together into nuclei and atoms are nuclei surrounded by a full complement of electrons. Hydrogen is composed of one proton and one electron. Helium is composed of two protons, two neutrons and two electrons. Carbon is composed of six protons, six neutrons and six electrons. Heavier elements, such as iron, lead and uranium, contain even larger numbers of protons, neutrons and electrons. Astronomers like to call all material made up of protons, neutrons and electrons "baryonic matter".

Until about thirty years ago, astronomers thought that the universe was composed almost entirely of this "baryonic matter", ordinary atoms. However, in the past few decades, there has been ever more evidence accumulating that suggests there is something in the universe that we can not see, perhaps some new form of matter.

WMAP AND DARK MATTER / DARK ENERGY

By making accurate measurements of the cosmic microwave background fluctuations, WMAP is able to measure the basic parameters of the Big Bang model including the density and composition of the universe. WMAP measures the relative density of baryonic and non-baryonic matter to an accuracy of better than a few percent of the overall density. It is also able to determine some of the properties of the non-baryonic matter: the interactions of the non-baryonic matter with itself, its mass and its interactions with ordinary matter all affect the details of the cosmic microwave background fluctuation spectrum.



WMAP determined that the universe is flat, from which it follows that the mean energy density in the universe is equal to the critical density (within a 1% margin of error). This is equivalent to a mass density of 9.9×10^{-30} g/cm^3, which is equivalent to only 5.9 protons per cubic meter. Of this total density, we now know the breakdown to be:

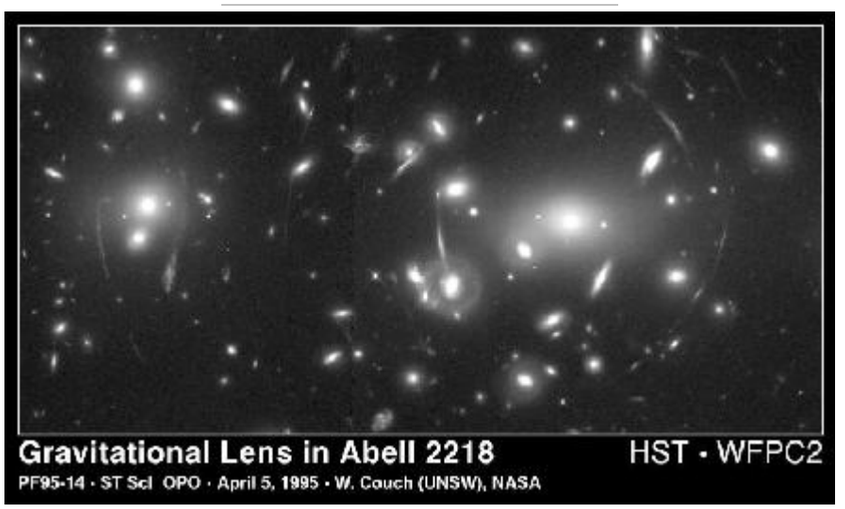
- 4.6% Atoms. More than 95% of the energy density in the universe is in a form that has never been directly detected in the laboratory! The actual density of atoms is equivalent to roughly 1 proton per 4 cubic meters.
- 23% Cold Dark Matter. Dark matter is likely to be composed of one or more species of sub-atomic particles that interact very weakly with ordinary matter. Particle physicists have many plausible candidates for the dark matter, and new particle accelerator experiments are likely to bring new insight in the coming years.
- 72% Dark Energy. The first observational hints of dark energy in the universe date back to the 1980's when astronomers were trying to understand how clusters of galaxies were formed. Their attempts to explain the observed distribution of galaxies were improved if dark energy was present, but the evidence was highly uncertain. In the 1990's, observations of supernova were used to trace the expansion history of the universe (over relatively recent times) and the big surprise was that the expansion appeared to be speeding up, rather than slowing down! There was some concern that the supernova data were being misinterpreted, but the result has held up to this day. In 2003, the first WMAP results came out indicating that the universe was flat (see above) and that the dark matter made up only ~23% of the density required to produce a flat universe. If 72% of the energy density in the universe is in the form of dark energy, which has a gravitationally repulsive effect, it is just the right amount to explain both the flatness of the universe and the observed accelerated expansion. Thus dark energy explains many cosmological observations at once.
- Fast moving neutrinos do not play a major role in the evolution of structure in the universe. They would have prevented the early clumping of gas in the universe, delaying the emergence of the first stars, in conflict with the WMAP data. However, with 5 years of data, WMAP is able to see evidence that a sea of cosmic neutrinos do exist in numbers that are expected from other lines of reasoning. This is the first time that such evidence has come from the cosmic microwave background.

ANOTHER PROBE OF DARK MATTER

By measuring the motions of stars and gas, astronomers can "weigh" galaxies. In our own solar system, we can use the velocity of the Earth around the Sun to measure the Sun's mass. The Earth moves around the Sun at 30 kilometers per second (roughly sixty thousand miles per hour). If the Sun were four times more massive, then the Earth would need to move around the Sun at 60 kilometers per second in order for it to stay on its orbit. The Sun moves around the Milky Way at 225 kilometers per second. We can use this velocity (and the velocity of other stars) to measure the mass of our Galaxy. Similarly, radio and optical observations of gas and stars in distant galaxies enable astronomers to determine the distribution of mass in these systems.

The mass that astronomers infer for galaxies including our own is roughly ten times larger than the mass that can be associated with stars, gas and dust in a Galaxy. This mass discrepancy has been confirmed by observations of gravitational lensing, the bending of light predicted by Einstein's theory of general relativity.

HST Image of a gravitational lens



Text Link for an HST press release describing this image.

By measuring how the background galaxies are distorted by the foreground cluster, astronomers can measure the mass in the cluster. The mass in the cluster is more than five times larger than the inferred mass in visible stars, gas and dust.

CANDIDATES FOR THE DARK MATTER

What is the nature of the "dark matter", this mysterious material that exerts a gravitational pull, but does not emit nor absorb light? Astronomers do not know.

There are a number of plausible speculations on the nature of the dark matter:

- Brown Dwarfs: if a star's mass is less than one twentieth of our Sun, its core is not hot enough to burn either hydrogen or deuterium, so it shines only by virtue of its gravitational contraction. These dim objects, intermediate between stars and planets, are not luminous enough to be directly detectable by our telescopes. Brown Dwarfs and similar objects have been nicknamed MACHOs (MAssive Compact Halo Objects) by astronomers. These MACHOs are potentially detectable by gravitational lensing experiments. If the dark matter is made mostly of MACHOs, then it is likely that baryonic matter does make up most of the mass of the universe.
- Supermassive Black Holes: these are thought to power distant k quasars. Some astronomers speculate that there may be copious numbers of black holes comprising the dark matter. These black holes are also potentially detectable through their lensing effects.
- New forms of matter: particle physicists, scientists who work to understand the fundamental forces of nature and the composition of matter, have speculated that there are new forces and new types of particles. One of the primary motivations for building "supercolliders" is to try to produce this matter in the laboratory. Since the universe was very dense and hot in the early moments following the Big Bang, the universe itself was a wonderful particle accelerator. Cosmologists speculate that the dark matter may be made of particles produced shortly after the Big Bang. These

particles would be very different from ordinary "baryonic matter". Cosmologists call these hypothetical particles WIMPs (for Weakly Interacting Massive Particles) or "non-baryonic matter".

DARK ENERGY: A COSMOLOGICAL CONSTANT?

Dark Energy makes up a large majority ot the total content of the universe, but this was not always known. Einstein first proposed the cosmological constant (not to be confused with the Hubble Constant) usually symbolized by the greek letter "lambda" (Λ), as a mathematical fix to the theory of general relativity. In its simplest form, general relativity predicted that the universe must either expand or contract. Einstein thought the universe was static, so he added this new term to stop the expansion. Friedmann, a Russian mathematician, realized that this was an unstable fix, like balancing a pencil on its point, and proposed an expanding universe model, now called the Big Bang theory. When Hubble's study of nearby galaxies showed that the universe was in fact expanding, Einstein regretted modifying his elegant theory and viewed the cosmological constant term as his "greatest mistake".

Many cosmologists advocate reviving the cosmological constant term on theoretical grounds, as a way to explain the rate of expansion of the universe. Modern field theory associates this term with the energy density of the vacuum. For this energy density to be comparable to other forms of matter in the universe, it would require new physics theories. So the addition of a cosmological constant term has profound implications for particle physics and our understanding of the fundamental forces of nature.

The main attraction of the cosmological constant term is that it significantly improves the agreement between theory and observation. The most spectacular example of this is the recent effort to measure how much the expansion of the universe has changed in the last few billion years. Generically, the gravitational pull exerted by the matter in the universe slows the expansion imparted by the Big Bang. Very recently it has become practical for astronomers to observe very bright rare stars called supernova in an effort to measure how much the universal expansion has slowed over the last few billion years. Surprisingly, the results of these observations indicate that the universal expansion is speeding up, or accelerating! While these results should be considered preliminary, they raise the possibility that the universe contains a bizarre form of matter or energy that is, in effect, gravitationally repulsive. The cosmological constant is an example of this type of energy. Much work remains to elucidate this mystery!

There are a number of other observations that are suggestive of the need for a cosmological constant. For example, if the cosmological constant today comprises most of the energy density of the universe, then the extrapolated age of the universe is much larger than it would be without such a term, which helps avoid the dilemma that the extrapolated age of the universe is younger than some of the oldest stars we observe! A cosmological constant term added to the standard model Big Bang theory leads to a model that appears to be consistent with the observed large-scale distribution of galaxies and clusters, with WMAP's measurements of cosmic microwave background fluctuations, and with the observed properties of X-ray clusters.

OTHER INTERESTING SITES AND FURTHER READING:

On dark matter:

- Visit the dark matter page at the Berkeley Cosmology Group.
- A list of popular books on dark matter and the Big Bang.
- A recent introductory html article by David Spergel on searching for dark matter. This article is geared towards physics undergraduates and will appear in "Some Outstanding Problems in Astrophysics", edited by J.N. Bahcall and J.P. Ostriker.

On MACHOs:

- OGLE home page: The Warsaw experiment searching for MACHOs.
- MACHO home page: The Berkeley/Livermore/Australia search for MACHOs.

On gravitational lensing:

- HST Gravitational Lensing Home Page.

Cosmological Constant:

- Donald Goldsmith, "Einstein's Greatest Blunder? The Cosmological Constant and Other Fudge Factors in the Physics of the Universe", (Harvard University Press: Cambridge, Mass.) A well written, popular account of the cosmological constant and the current state of cosmology.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

How Fast is the Universe Expanding?

The expansion or contraction of the universe depends on its content and past history. With enough matter, the expansion will slow or even become a contraction. On the other hand, dark energy drives the universe towards increasing rates of expansion. The current rate of expansion is usually expressed as the Hubble Constant (in units of kilometers per second per Megaparsec, or just per second).

Hubble found that the universe was not static, but rather was expanding!

HISTORICAL OVERVIEW

In the 1920s, Edwin Hubble, using the newly constructed 100" telescope at Mount Wilson Observatory, detected variable stars in several nebulae. Nebulae are diffuse objects whose nature was a topic of heated debate in the astronomical community: were they interstellar clouds in our own Milky Way galaxy, or whole galaxies outside our galaxy? This was a difficult question to answer because it is notoriously difficult to measure the distance to most astronomical bodies since there is no point of reference for comparison. Hubble's discovery was revolutionary because these variable stars had a characteristic pattern resembling a class of stars called Cepheid variables. Earlier, Henrietta Levitt, part of a group of female astronomers working at Harvard College Observatory, had shown there was a tight correlation between the period of a Cepheid variable star and its luminosity (intrinsic brightness). By knowing the luminosity of a source it is possible to measure the distance to that source by measuring how bright it appears to us: the dimmer it appears the farther away it is. Thus, by measuring the period of these stars (and hence their luminosity) and their apparent brightness, Hubble was able to show that these nebula were not clouds within our own Galaxy, but were external galaxies far beyond the edge of our own Galaxy.

Hubble's second revolutionary discovery was based on comparing his measurements of the Cepheid-based galaxy distance determinations with measurements of the relative velocities of these galaxies. He showed that more distant galaxies were moving away from us more rapidly:

$$v = H_o d$$

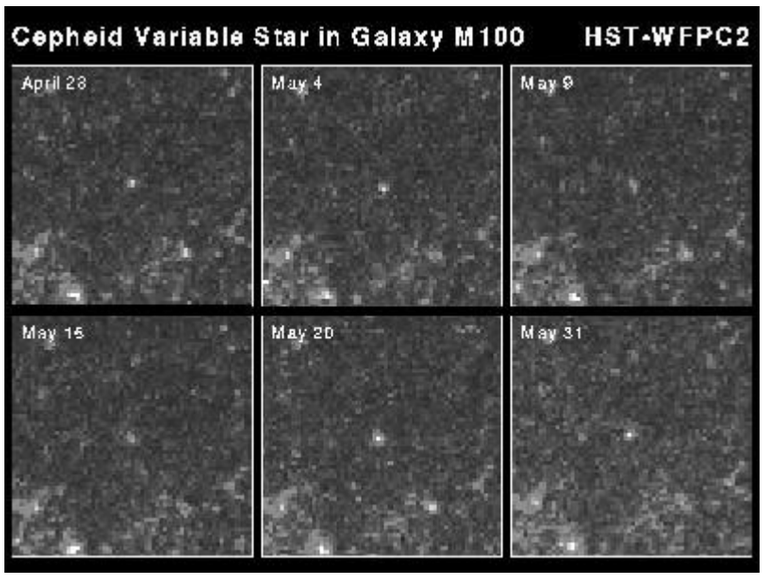
where v is the speed at which a galaxy moves away from us, and d is its distance. The constant of proportionality H_o is now called the Hubble constant. The common unit of velocity used to measure the speed of a galaxy is km/sec, while the most common unit of for measuring the distance to nearby galaxies is called the Megaparsec (Mpc) which is equal to 3.26 million light years or 30,800,000,000,000,000,000 km! Thus the units of the Hubble constant are (km/sec)/Mpc.

This discovery marked the beginning of the modern age of cosmology. Today, Cepheid variables remain one of the best methods for measuring distances to galaxies and are vital to determining the expansion rate (the Hubble constant) and age of the universe.

WHAT ARE CEPHEID VARIABLES?

The structure of all stars, including the Sun and Cepheid variable stars, is determined by the opacity of matter in the star. If the matter is very opaque, then it takes a long time for photons to diffuse out from the hot core of the star, and strong temperature and pressure gradients can develop in the star. If the matter is nearly transparent, then photons move easily through the star and erase any temperature gradient. Cepheid stars oscillate between two states: when the star is in its compact state, the helium in a layer of its atmosphere is singly ionized. Photons scatter off of the bound electron in the singly ionized helium atoms, thus, the layer is very opaque and large temperature and pressure gradients build up across the layer. These large pressures cause the layer (and the whole star) to expand. When the star is in its expanded state, the helium in the layer is doubly ionized, so that the layer is more transparent to radiation and there is much weaker pressure gradient across the layer. Without the pressure gradient to support the star against gravity, the layer (and the whole star) contracts and the star returns to its compressed state.

Cepheid variable stars have masses between five and twenty solar masses. The more massive stars are more luminous and have more extended envelopes. Because their envelopes are more extended and the density in their envelopes is lower, their variability period, which is proportional to the inverse square root of the density in the layer, is longer.



Text Link to the HST press release describing this image.

DIFFICULTIES IN USING CEPHEIDS

There have been a number of difficulties associated with using Cepheids as distance indicators. Until recently, astronomers used photographic plates to measure the fluxes from stars. The plates were highly non-linear and often produced faulty flux measurements. Since massive stars are short lived, they are always located near their dusty birthplaces. Dust absorbs light, particularly at blue wavelengths where most photographic images were taken, and if not properly corrected for, this dust absorption can lead to erroneous luminosity determinations. Finally, it has been very difficult to detect Cepheids in distant galaxies from the ground: Earth's fluctuating atmosphere makes it impossible to separate these stars from the diffuse light of their host galaxies.

Another historic difficulty with using Cepheids as distance indicators has been the problem of determining the distance to a sample of nearby Cepheids. In recent years, astronomers have developed several very reliable and independent methods of determining the distances to the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC), two of the nearby satellite galaxies of our own Milky Way Galaxy. Since the LMC and SMC contain large number of Cepheids, they can be used to calibrate the distance scale.

RECENT PROGRESS

Recent technological advances have enabled astronomers to overcome a number of the other past difficulties. New detectors called CCDs (charge coupled devices) made possible accurate flux measurements. These detectors are also sensitive in the infrared wavelengths. Dust is much more transparent at these wavelengths. By measuring fluxes at multiple wavelengths, astronomers were able to correct for the effects of dust and make much more accurate distance determinations.

These advances enabled more accurate study of the nearby galaxies that comprise the "Local Group" of galaxies. Astronomers observed Cepheids in both the metal rich inner region of the Andromeda galaxy and its metal poor outer region. (To an astronomer, a "metal" is any element heavier than helium - the second lightest element in the periodic table. Such elements are produced in stars and are ultimately released into the interstellar medium as the stars evolve.) This work showed that the properties of Cepheids did not depend sensitively on chemical abundances. Despite these advances, astronomers, limited by the Earth's atmosphere, could only measure the distances to the nearest galaxies. In addition to the motion due to the expansion of the universe, galaxies have "relative motions" due to the gravitational pull of their neighbors. Because of these "peculiar motions", astronomers need to measure the distances to distant galaxies so that they can determine the Hubble constant.

Trying to push deeper into the universe, astronomers have developed a number of new techniques for determining relative distances to galaxies: these independent relative distance scales now agree to better than 10%. For example, there is a very tight relation, called the Tully-Fisher relation, between the rotational velocity of a spiral galaxy and its luminosity. Astronomers also found that Type Ia supernova, which are thought to be due to the explosive burning of a white dwarf star, all had nearly

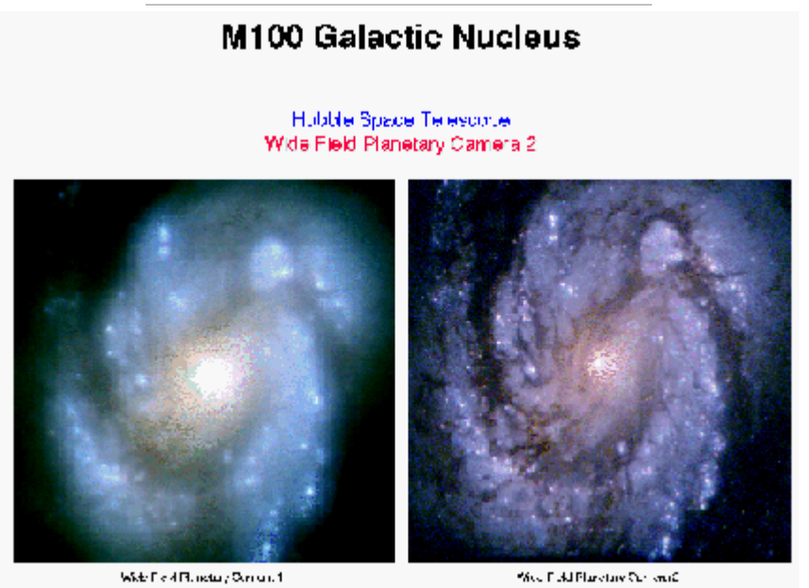
the same peak luminosity. However, without accurate measurements of distance to large numbers of prototype galaxies, astronomers could not calibrate these relative distance measurements. Thus, they were unable to make accurate determinations of the Hubble constant.

Over the past few decades, leading astronomers, using different data, reported values for the Hubble constant that varied between 50 (km/sec)/Mpc and 100 (km/sec)/Mpc. Resolving this factor of two discrepancy was one of the most important outstanding problems in observational cosmology.

HUBBLE KEY PROJECT

One of the "key projects" of the Hubble Space Telescope was to complete Edwin Hubble's program of measuring distances to nearby galaxies. While the Hubble Space Telescope (HST) is comparable in diameter to Hubble's telescope on Mount Wilson, it had the advantage of being above the Earth's atmosphere, rather then being located on the outskirts of Los Angeles. NASA's repair of the Hubble Space Telescope restored its vision and enabled the key project program. The photos below show before and after images of M100, one of the nearby galaxies observed by the key project program. With the refurbished HST, it was much easier to detect individual bright stars in M100, a necessary step in studying Cepheid variables. The project also checked to see if the properties of Cepheid variables are sensitive to stellar composition.

HST image of M100 before and after repair



Text Link to the HST press release describing this image.

Overall, the key project attempted to get distances to 20 nearby galaxies. With this large sample, the project calibrated and cross checked a number of the secondary distance indicators. Because M100 is close enough to us that its peculiar motion is a significant fraction of its Hubble expansion velocity, the key project team used relative distance indicators to extrapolate from the Virgo cluster, a nearby cluster of galaxies containing M100, to the more distant Coma cluster and to obtain a measurement of the Hubble constant of 70 (km/sec)/Mpc, with an uncertainty of 10%.

The key project determination of the Hubble constant is consistent with a number of independent efforts to estimate the Hubble constant: a statistical synthesis by G.F.R. Ellis and his collaborators of the published literature yielded a value between 66 and 82 (km/sec)/Mpc. However, there was still not complete consensus on the value of the Hubble constant.

WMAP AND THE HUBBLE CONSTANT

By characterizing the detailed structure of the cosmic microwave background fluctuations, WMAP has accurately determined the basic cosmological parameters, including the Hubble constant, to better than 5%. This measurement is completely independent of traditional measurements using Cepheid variables and other techniques. The current results show the Hubble Constant to be 73.5 (km/sec)/Mpc (give or take 3.2 (km/sec)/Mpc). If the WMAP data is combined with other cosmological data, the best estimate is 70.8 (km/sec)/Mpc (give or take 1.6 (km/sec)/Mpc). These results assume that the universe is spatially flat, which is consistent with all available data. However, if we do not make this assumption, the uncertainty in the Hubble constant

increases to 4 (km/sec)/Mpc, or slightly over 5%.

Parts of this page were adapted from the article "**The age of the universe**", D.N. Spergel, M. Bolte (UC, Santa Cruz) and W. Freedman (Carnegie Observatories). Proc. Natl. Acad. Sci. USA, Vol. 94, pp. 6579-6584, June 1997.

FURTHER READING:

- More on the Hubble Constant from Space Telescope Science Institute including movies.
- Freedman, Wendy L., "The Expansion Rate and Science of the Universe", Scientific American, Nov. 1992.
- Osterbrock, D.E., Gwinn, J.A. & Brashear, R.S., "Hubble and the Expanding Universe", Scientific American, July 1993.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

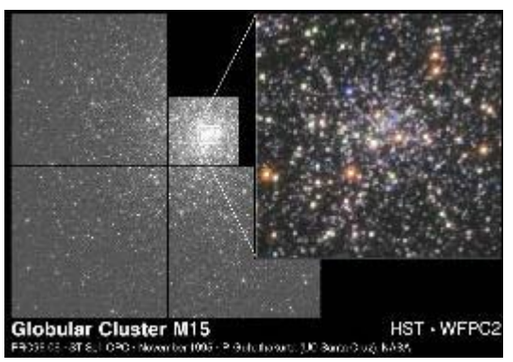
Wilkinson Microwave Anisotropy Probe

How Old is the Universe?

Until recently, astronomers estimated that the Big Bang occurred between 12 and 14 billion years ago. To put this in perspective, the Solar System is thought to be 4.5 billion years old and humans have existed as a genus for only a few million years. Astronomers estimate the age of the universe in two ways: 1) by looking for the oldest stars; and 2) by measuring the rate of expansion of the universe and extrapolating back to the Big Bang; just as crime detectives can trace the origin of a bullet from the holes in a wall.

OLDER THAN THE OLDEST STARS?

Astronomers can place a lower limit to the age of the universe by studying globular clusters. Globular clusters are a dense collection of roughly a million stars. Stellar densities near the center of the globular cluster are enormous. If we lived near the center of one, there would be several hundred thousand stars closer to us than Proxima Centauri, the star nearest to the Sun.



Text Link to the HST press release describing this image

The life cycle of a star depends upon its mass. High mass stars are much brighter than low mass stars, thus they rapidly burn through their supply of hydrogen fuel. A star like the Sun has enough fuel in its core to burn at its current brightness for approximately 9 billion years. A star that is twice as massive as the Sun will burn through its fuel supply in only 800 million years. A 10 solar mass star, a star that is 10 times more massive than the Sun, burns nearly a thousand times brighter and has only a 20 million year fuel supply. Conversely, a star that is half as massive as the Sun burns slowly enough for its fuel to last more than 20 billion years.

All of the stars in a globular cluster formed at roughly the same time, thus they can serve as cosmic clocks. If a globular cluster is more than 20 million years old, then all of its hydrogen burning stars will be less massive than 10 solar masses. This implies that no individual hydrogen burning star will be more than 1000 times brighter than the Sun. If a globular cluster is more than 2 billion years old, then there will be no hydrogen-burning star more massive than 2 solar masses.

The oldest globular clusters contain only stars less massive than 0.7 solar masses. These low mass stars are much dimmer than the Sun. This observation suggests that the oldest globular clusters are between 11 and 18 billion years old. The uncertainty in this estimate is due to the difficulty in determining the exact distance to a globular cluster (hence, an uncertainty in the brightness (and mass) of the stars in the cluster). Another source of uncertainty in this estimate lies in our ignorance of some of the finer details of stellar evolution. Presumably, the universe itself is at least as old as the oldest globular clusters that reside in it.

EXTRAPOLATING BACK TO THE BIG BANG

An alternative approach to estimating is the age of the universe is to measure the “Hubble constant”. The Hubble constant is a measure of the current expansion rate of the universe. Cosmologists use this measurement to extrapolate back to the Big Bang. This extrapolation depends on the history of the expansion rate which in turn depends on the current density of the universe and on the composition of the universe.

If the universe is flat and composed mostly of matter, then the age of the universe is

$$2/(3\ H_o)$$

where H_o is the value of the Hubble constant.

If the universe has a very low density of matter, then its extrapolated age is larger:

$$1/H_o$$

If the universe contains a form of matter similar to the cosmological constant, then the inferred age can be even larger.

Many astronomers are working hard to measure the Hubble constant using a variety of different techniques. Until recently, the best estimates ranged from 65 km/sec/Megaparsec to 80 km/sec/Megaparsec, with the best value being about 72 km/sec/Megaparsec. In more familiar units, astronomers believe that $1/H_o$ is between 12 and 14 billion years.

AN AGE CRISIS?

If we compare the two age determinations, there is a potential crisis. If the universe is flat, and dominated by ordinary or dark matter, the age of the universe as inferred from the Hubble constant would be about 9 billion years. The age of the universe would be shorter than the age of oldest stars. This contradiction implies that either 1) our measurement of the Hubble constant is incorrect, 2) the Big Bang theory is incorrect or 3) that we need a form of matter like a cosmological constant that implies an older age for a given observed expansion rate.

Some astronomers believe that this crisis will pass as soon as measurements improve. If the astronomers who have measured the smaller values of the Hubble constant are correct, and if the smaller estimates of globular cluster ages are also correct, then all is well for the Big Bang theory, even without a cosmological constant.

WMAP CAN MEASURE THE AGE OF THE UNIVERSE

Measurements by the WMAP satellite can help resolve this crisis. If current ideas about the origin of large-scale structure are correct, then the detailed structure of the cosmic microwave background fluctuations will depend on the current density of the universe, the composition of the universe and its expansion rate. WMAP has been able to determine these parameters with an accuracy of better than than 3% of the critical density. In turn, knowing the composition with this precision, we can estimate the age of the universe to about 1%: 13.7 ± 0.13 billion years!

How does WMAP data enable us to determine the age of the universe is 13.7 billion years, with an uncertainty of 1%? The key to this is that by knowing the composition of matter and energy density in the universe, we can use Einstein's General Relativity to compute how fast the universe has been expanding in the past. With that information, we can turn the clock back and determine when the universe had "zero" size, according to Einstein. The time between then and now is the age of the universe. There is one caveat to keep in mind that affects the certainty of the age determination: we assume that the universe is flat, which is well supported by WMAP and other data. If we relax this assumption within the allowed range, the uncertainty increases to a bit over 2%. However, theorists have long known that a nearly-flat universe is very difficult to produce, whereas inflation naturally predicts a flat universe.

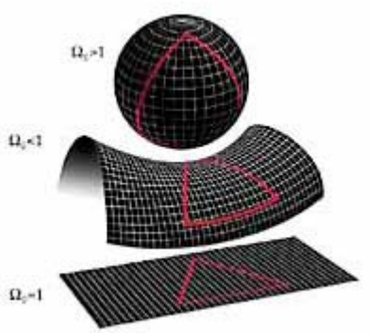
The expansion age measured by WMAP is larger than the oldest globular clusters, so the Big Bang theory has passed an important test using data independent of the type collected by WMAP. If the expansion age measured by WMAP had been smaller than the oldest globular clusters, then there would have been something fundamentally wrong about either the Big Bang theory or the theory of stellar evolution. Either way, astronomers would have needed to rethink many of their cherished ideas. But our current estimate of age fits well with what we know from other kinds of measurements.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Monday, 07-19-2010

Will the Universe expand forever?

The fate of the universe is determined by a struggle between the momentum of expansion and the pull of gravity. The rate of expansion is expressed by the Hubble Constant, H_0, while the strength of gravity depends on the density and pressure of the matter in the universe. If the pressure of the matter is low, as is the case with most forms of matter we know of, then the fate of the universe is governed by the density. If the density of the universe is less than the "critical density" which is proportional to the square of the Hubble constant, then the universe will expand forever. If the density of the universe is greater than the "critical density", then gravity will eventually win and the universe will collapse back on itself, the so called "Big Crunch". However, the results of the WMAP mission and observations of distant supernova have suggested that the expansion of the universe is actually accelerating which implies the existence of a form of matter with a strong negative pressure, such as the cosmological constant. This strange form of matter is also sometimes referred to as "dark energy". If dark energy in fact plays a significant role in the evolution of the universe, then in all likelihood the universe will continue to expand forever.

INFINITE UNIVERSE?



The density of the universe also determines its geometry. If the density of the universe exceeds the critical density, then the geometry of space is closed and positively curved like the surface of a sphere. This implies that initially parallel photon paths converge slowly, eventually cross, and return back to their starting point (if the universe lasts long enough). If the density of the universe is less than the critical density, then the geometry of space is open (infinite), and negatively curved like the surface of a saddle. If the density of the universe exactly equals the critical density, then the geometry of the universe is flat like a sheet of paper, and infinite in extent.

The simplest version of the inflationary theory, an extension of the Big Bang theory, predicts that the density of the universe is very close to the critical density, and that the geometry of the universe is flat, like a sheet of paper.

MEASUREMENTS FROM WMAP

The WMAP spacecraft can measure the basic parameters of the Big Bang theory including the geometry of the universe. If the universe were flat, the brightest microwave background fluctuations (or "spots") would be about one degree across. If the universe were open, the spots would be less than one degree across. If the universe were closed, the brightest spots would be greater than one degree across.

Recent measurements (c. 2001) by a number of ground-based and balloon-based experiments, including MAT/TOCO, Boomerang, Maxima, and DASI, have shown that the brightest spots are about 1 degree across. Thus the universe was known to be flat to within about 15% accuracy prior to the WMAP results. WMAP has confirmed this result with very high accuracy and precision. We now know that the universe is flat with only a 0.5% margin of error. This suggests that the Universe is infinite in extent; however, since the Universe has a finite age, we can only observe a finite volume of the Universe. All we can truly conclude is that the Universe is much larger than the volume we can directly observe.

Wilkinson Microwave Anisotropy Probe

What is a Cosmological Constant?

Einstein first proposed the cosmological constant (not to be confused with the Hubble Constant) usually symbolized by the greek letter "lambda" (Λ), as a mathematical fix to the theory of general relativity. In its simplest form, general relativity predicted that the universe must either expand or contract. Einstein thought the universe was static, so he added this new term to stop the expansion. Friedmann, a Russian mathematician, realized that this was an unstable fix, like balancing a pencil on its point, and proposed an expanding universe model, now called the Big Bang theory. When Hubble's study of nearby galaxies showed that the universe was in fact expanding, Einstein regretted modifying his elegant theory and viewed the cosmological constant term as his "greatest mistake".

Many cosmologists advocate reviving the cosmological constant term on theoretical grounds. Modern field theory associates this term with the energy density of the vacuum. For this energy density to be comparable to other forms of matter in the universe, it would require new physics: the addition of a cosmological constant term has profound implications for particle physics and our understanding of the fundamental forces of nature.

The main attraction of the cosmological constant term is that it significantly improves the agreement between theory and observation. The most spectacular example of this is the recent effort to measure how much the expansion of the universe has changed in the last few billion years. Generically, the gravitational pull exerted by the matter in the universe slows the expansion imparted by the Big Bang. Very recently it has become practical for astronomers to observe very bright rare stars called supernova in an effort to measure how much the universal expansion has slowed over the last few billion years. Surprisingly, the results of these observations indicate that the universal expansion is speeding up, or accelerating! While these results should be considered preliminary, they raise the possibility that the universe contains a bizarre form of matter or energy that is, in effect, gravitationally repulsive. The cosmological constant is an example of this type of energy. Much work remains to elucidate this mystery!

There are a number of other observations that are suggestive of the need for a cosmological constant. For example, if the cosmological constant today comprises most of the energy density of the universe, then the extrapolated age of the universe is much larger than it would be without such a term, which helps avoid the dilemma that the extrapolated age of the universe is younger than some of the oldest stars we observe! A cosmological constant term added to the standard model Big Bang theory leads to a model that appears to be consistent with the observed large-scale distribution of galaxies and clusters, with WMAP's measurements of cosmic microwave background fluctuations, and with the observed properties of X-ray clusters.

WMAP AND THE COSMOLOGICAL CONSTANT

By characterizing the detailed structure of the cosmic microwave background fluctuations, WMAP is able to accurately determine the basic cosmological parameters, including the cosmological constant, to better than 5%.

FURTHER READING:

- Donald Goldsmith, "Einstein's Greatest Blunder? The Cosmological Constant and Other Fudge Factors in the Physics of the Universe", (Harvard University Press: Cambridge, Mass.) A well written, popular account of the cosmological constant and the current state of cosmology.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

Understanding the Evolution of Life in the Universe

HOW DID THE UNIVERSE START AND EVOLVE?

WMAP found that the universe is 13.7 billion years old. The universe began with an unimaginably enormous density and temperature. This immense primordial energy was the cauldron from whence all life arose. Elementary particles were created and destroyed by the ultimate particle accelerator in the first moments of the universe.

There was matter and there was antimatter. When they met, they annihilated each other and created light. Somehow, it seems that there was a tiny fraction more matter than antimatter, so when nature took its course, the universe was left with some matter, no antimatter, and a tremendous amount of light. Today, WMAP measures that there is more than a billion times more light than matter.

WE AREN'T MADE OF HYDROGEN!

WMAP determined that about 4.6% of the mass and energy of the universe is contained in atoms (protons and neutrons). All of life is made from a portion of this 4.6%.

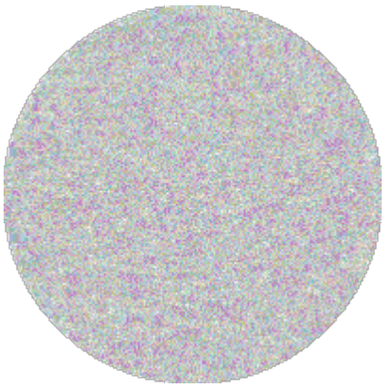
The only chemical elements created at the beginning of our universe were hydrogen, helium and lithium, the three lightest atoms in the periodic table. These elements were formed throughout the universe as a hot gas. It's possible to imagine a universe where elements heavier than lithium would never form and life never develop. But that is not what happened in our universe.

We are carbon-based life forms. We are made of and drink water (H_2O). We breathe oxygen.

Carbon and oxygen were not created in the Big Bang, but rather much later in stars. All of the carbon and oxygen in all living things are made in the nuclear fusion reactors that we call stars. The early stars are massive and short-lived. They consume their hydrogen, helium and lithium and produce heavier elements. When these stars die with a bang they spread the elements of life, carbon and oxygen, throughout the universe. New stars condense and new planets form from these heavier elements. The stage is set for life to begin. Understanding when and how these events occur offer another window on the evolution of life in our universe.

WMAP determined that the first stars in the universe arose only about 400 million years after the Big Bang. But what made the stars?

THINGS THAT GO BUMP IN THE NIGHT.



Quantum Fluctuations are the random nature of matter's state of existence or nonexistence. At these incredibly small sub-atomic scales, the state of reality is fleeting, changing from nanosecond to nanosecond.

The motor for making stars (and galaxies) came early and was very subtle. Before the completion of the first fraction of a second of the universe, sub-atomic scale activity, tiny "quantum fluctuations", drove the universe towards stars and life. With the sudden expansion of a pinhead size portion of the universe in a fraction of a second, random quantum fluctuations inflated rapidly from the tiny quantum world to a macroscopic landscape of astronomical proportions. Why do we believe this? Because the microwave afterglow light from the Big Bang has an extraordinarily uniform temperature across the sky. There has not been time for the different parts of the universe to come into an equilibrium with each other *unless* the regions had exponentially inflated from a tiny patch. The only way the isotropy (uniformity) could have arisen is if the different regions were in thermal equilibrium with each other early in the history of the universe, and then rapidly inflated apart. WMAP has verified that other predictions from the inflation theory also appear to be true..

As the universe inflated, the tiny quantum fluctuations grew to become tiny variations in the amount of matter from one place to another. A tiny amount is all it takes for gravity to do its thing. Gravity is one of the basic forces of nature and controls the evolution of the large scale structure of the universe. Without gravity there would be no stars or planets, only a cold thin mist of particles. Without the variations in the particle soup initiated by the quantum fluctuations, gravity could not begin to concentrate tiny amounts of matter into even larger amounts of matter. The end result of the pull of gravity: galaxies, stars and planets. The fluctuations, mapped in detail by the WMAP mission, are the factories and cradles of life.

THE RECIPE FOR LIFE REQUIRES A DELICATE BALANCE OF COSMIC INGREDIENTS.

The differences in the early soup of universe particles were very small, so large scale changes take time to manifest themselves. What if our universe had only lasted for a second, or a year, or one million years? The age of the universe is controlled by the basic rules that govern matter, energy, and time. We needed almost 13.7 billion years to evolve and come to recognize this fact.

How long the universe lasts and how it evolves depends on its total energy and matter content. A universe with enormously more matter than ours would rapidly collapse back under its own gravity well before life could form. A very long lived universe might not have enough mass for stars to ever form. In addition, WMAP has confirmed the existence of a dark energy that acts like an anti-gravity, driving the universe to accelerate its expansion. Had the dark energy dominated earlier, the universe would have expanded too rapidly to support the development of life. Our universe seems to have Goldilocks properties: not too much and not too little -- just enough mass and energy to support the development of life.

IS THERE OTHER INTELLIGENT LIFE IN THE UNIVERSE?

We don't know whether or not there is other intelligent life in the universe. There is no reason there shouldn't be. We know by our own existence that the universe is conducive to life. But there are many hurdles to overcome for intelligent life to form, and many threats to its continued existence once it does form. Life constantly faces the prospect of extinction. Life requires energy, water, and carbon; an environmental disaster that removes water, dooms life. Other environment disasters threaten. On Earth we have had huge meteor impacts that are believed to have caused mass extinctions. The harsh radiation of space is blocked only by Earth's atmosphere and magnetic field. Environmental instabilities cause ice ages. One day, billions of years from now, our Sun will burn out. Other, heavier stars end their lives in explosions called supernovae; the blast and radiation from a

nearby supernova could destroy all life on Earth.

The dark energy will inexorably stretch the universe into an icy cold end. Since we don't know what the dark energy is, this might be wrong, but no less deadly depending on how the nature of the dark energy changes.

Many people are engaged in efforts to detect life in the universe. There are two strategies: we look for it, or it finds us. Perhaps a middle ground would be if we detected signals coming from life elsewhere in the universe. The Search for Extraterrestrial Intelligence (SETI) program pioneered searches for life. WMAP itself is, in a small way, a mini-SETI experiment, since it constantly scans the skies over a wide range of microwave frequencies. WMAP was not optimized to search for life. Other efforts are (have been). Some day, we may know for sure whether we are alone in the universe. In the meantime the search goes on, as we also try to understand the universe and how it may be conducive to life.

By detecting and measuring the density fluctuations in the cosmic microwave background using the WMAP space mission we are learning about the early universe; and we begin to understand the basic ingredients that make life possible. In the future, we would like to enhance these efforts with other missions, such as NASA's Einstein Inflation Probe, which would strive to detect the gravity disturbances from the era when the universe originally inflated. This passionate search for knowledge is characteristic of human life.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 10-15-2010

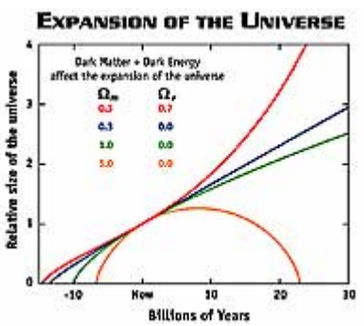
Wilkinson Microwave Anisotropy Probe

What is the Ultimate Fate of the Universe?

"Some Say the World Will End in Fire, Others Say in Ice"

Just as Robert Frost imagined two possible fates for the Earth in his poem, cosmologists envision two possible fates for the universe:

- Endless expansion
- The “Big Crunch”


EXPANSION OF THE UNIVERSE
Dark Matter + Dark Energy
affect the expansion of the universe
Relative size of the universe
Billions of Years
Now

The evolution of the universe is determined by a struggle between the momentum of expansion and the pull (or push!) of gravity. The current rate of expansion is measured by the Hubble Constant, while the strength of gravity depends on the density and pressure of the matter in the universe. If the pressure of the matter is low, as is the case with most forms of matter we know of, then the fate of the universe is governed by the density.

If the density of the universe is less than the critical density, then the universe will expand forever, like the green or blue curves in the graph above. Gravity might slow the expansion rate down over time, but for densities below the critical density, there isn’t enough gravitational pull from the material to ever stop or reverse the outward expansion. This is also known as the “Big Chill” or “Big Freeze” because the universe will slowly cool as it expands until eventually it is unable to sustain any life.

If the density of the universe is greater than the critical density, then gravity will eventually win and the universe will collapse back on itself, the so called “Big Crunch”, like the graph's orange curve. In this universe, there is sufficient mass in the universe to slow the expansion to a stop, and then eventually reverse it.

Recent observations of distant supernova have suggested that the expansion of the universe is actually accelerating or speeding up, like the graph's red curve, which implies the existence of a form of matter with a strong negative pressure, such as the cosmological constant. This strange form of matter is also sometimes referred to as the “dark energy”. Unlike gravity which works to slow the expansion down, dark energy works to speed the expansion up. If dark energy in fact plays a significant role in the evolution of the universe, then in all likelihood the universe will continue to expand forever.

There is a growing consensus among cosmologists that the total density of matter is equal to the critical density, so that the universe is spatially flat. Approximately 3/10 of this is in the form of a low pressure matter, most of which is thought to be “non-baryonic” dark matter, while the remaining 7/10 is thought to be in the form of a negative pressure “dark energy”, like the cosmological constant. If this is true, then dark energy is the major driving force behind the fate of the universe and it will expand forever exponentially.

MEASUREMENTS FROM WMAP

The WMAP satellite measures the basic parameters of the Big Bang theory including the fate of the universe. The results suggest the geometry of the universe is flat and will expand forever. Further study of the dark energy with future experiments and space missions is needed to understand its nature and effect on the rate of future expanison.

OTHER INTERESTING SITES:

On cosmology with supernovae:

- The Supernova Cosmology Project: the LBL program to measure the expansion history.
- The High-Z Supernova Search: the multi-national program to measure the expansion history.
- The SNAP mission: a proposed satellite mission to study cosmology with supernovae.

On runaway expansion:

- The fate of the *contents* of the universe is described in a nice timeline from the NOVA show The Runaway Universe.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Thursday, 08-19-2010

Wilkinson Microwave Anisotropy Probe

Related Topics

The following pages are not central to an understanding of the universe as a whole. Rather, they are intended to describe some of the more interesting objects within our universe.

First objects
: When did the first objects form in the universe?

The Milky Way galaxy
: A brief tour of our own Milky Way galaxy, with a beautiful image of it from the COBE satellite.

The life cycle of stars
: Learn how stars form, live and die.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

When Did the First Cosmic Structures Form?

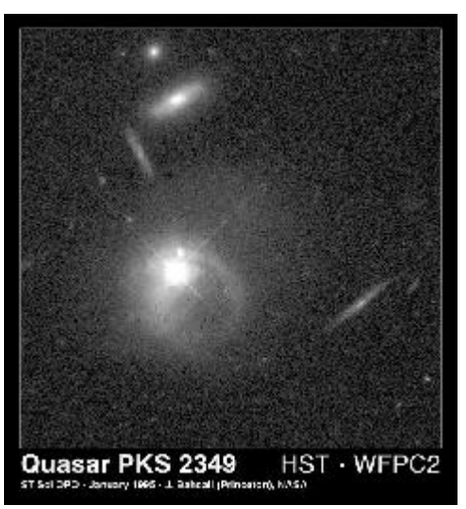
Quasars are the most distant distinct objects that astronomers have been able to directly detect. Because of their intrinsic brightness, the most distant quasars are seen at a time when the universe was one tenth its present age, roughly a billion years after the Big Bang. However, astronomers believe that some objects must have formed earlier than quasars, because the ambient gas in the universe is observed to be ionized at a relatively early time, presumably due to ionizing radiation from a population of early objects. Since ionized gas can interact with cosmic microwave background photons, WMAP observations help to elucidate the nature of the ionized gas and the objects that caused the ionization.

QUASARS

Since light travels at a finite speed, distant objects are seen as they existed in the past. We see the Sun not as it is now, but how it was eight minutes ago. (The Sun is eight light minutes away from the Earth). We see the nearby stars as they were several years ago. We see Andromeda, the nearest spiral galaxy as it was roughly 2.5 million years ago. Thus, the most distant objects that we see are the oldest objects that we can directly detect.

Quasars are the most distant distinct objects that astronomers have been able to detect. In a region smaller than our solar system, a quasar emits more light than our entire Milky Way galaxy. Quasars are believed to be supermassive black holes, whose masses exceed that of a million Suns, and whose pull is swallowing gas and stars from their host galaxies. They shine brightly by converting the gravitational energy of the infalling material into light. The most distant quasars are seen at a time when the universe was one tenth its present age, roughly a billion years after the Big Bang.

HST IMAGE OF A QUASAR INTERACTING WITH A GALAXY:



Text Link to HST press release describing this picture

Since light from a quasar illuminates all of the material along its path to us, quasars serve as distant flashlights revealing the properties of the early universe. By observing quasars, astronomers have learned that almost all of the hydrogen gas in the early universe was ionized into protons and free electrons within a billion years after the Big Bang. They have also inferred that the known quasars were not energetic enough nor common enough to ionize all of the gas in the visible universe.

WHAT IONIZED THE GAS IN THE EARLY UNIVERSE?

Astronomers are not certain what objects ionized the gas in the early universe nor do they know when this ionization occurred. Some speculate that an early generation of massive stars ionized the gas. Others speculate that most galaxies contain supermassive black holes and that the formation of these supermassive black holes illuminated the early universe.

WHEN WAS THE GAS IONIZED?

While observations of quasars enable astronomers to infer that the gas was ionized within the first billion years of the universe, we need to observe something more distant than quasars to learn when the gas was first ionized: the cosmic microwave background radiation. Since the cosmic microwave background photons were emitted roughly 380,000 years after the Big Bang, much earlier than the photons from quasars, their properties tell us about the subsequent evolutionary history of the universe. Microwave photons move freely through neutral gas, but they scatter off of ionized gas. This scattering reduces the amplitude of fluctuations in the temperature of the cosmic microwave background and produces new "polarized" microwave background fluctuations.

Scattered light is often polarized. On a bright day, we see not only sunlight directly from the Sun, but also light that scatters off of dust in the air. This scattered light, or "glare", is polarized and can thus be filtered out by a good pair of polarized sunglasses. Similarly, scattered cosmic microwave background photons are polarized by scattering off of free electrons in the early universe. WMAP is designed to detect polarized photons. In principal, their properties reveal the number of free electrons in the early universe and the ionization history of the universe. This enables astronomers to infer that the first objects in the universe capable of ionizing the gas formed at about 400 million years after the Big Bang. We hope that the time history of the ionization will help determine the nature of these first objects.

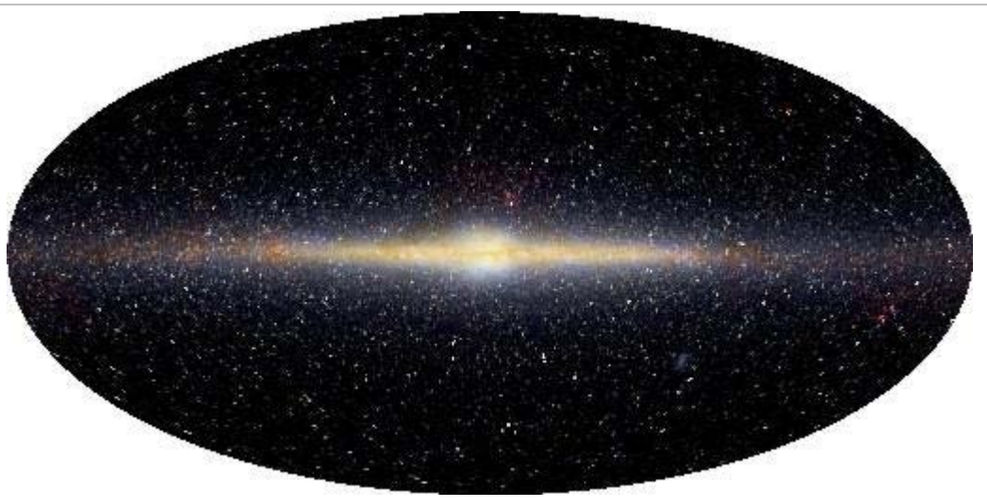
wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

The Milky Way

The Milky Way is a gravitationally bound collection of roughly a hundred billion stars. Our Sun is one of these stars and is located roughly 24,000 light years (or 8000 parsecs) from the center of our the Milky Way.

COBE image of the Milky Way: (Courtesy of Ned Wright, click here for related images)



The Galaxy has three major components:

- A thin disk consisting of young and intermediate age stars - this disk also contains gas and is actively forming new stars. Dust in the disk makes it appear orange in the picture. Dust absorbs blue light more than red light and thus makes stars appear reddish. Our Galaxy has spiral arms in its disk - these spiral arms are regions of active star formation.
- A bar of older stars (white in the COBE picture).
- An extended dark halo whose composition is unknown. Since the matter in the halo does not consist of luminous stars, it does not show up in the COBE image. The existence of the dark halo is inferred from its gravitational pull on the visible matter.

Additional images of the sky from the COBE-Dirbe experiment.

FURTHER READING:

- Frommert, H. & Kronberg, C., " The Milky Way Galaxy", extensive web-based material.
- van den Bergh, S. & Hesser, J.E., "How the Milky Way Formed", Scientific American, January 1993.
- Ferris, Timothy, "Coming of Age in the Milky Way", An excellent popular astronomy book.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Monday, 06-28-2010

Wilkinson Microwave Anisotropy Probe

The Life and Death of Stars

WHERE ARE STARS BORN?

Astronomers believe that molecular clouds, dense clouds of gas located primarily in the spiral arms of galaxies are the birthplace of stars. Dense regions in the clouds collapse and form "protostars". Initially, the gravitational energy of the collapsing star is the source of its energy. Once the star contracts enough that its central core can burn hydrogen to helium, it becomes a "main sequence" star.

Image of "Star Birth" Clouds in M16:

PRC95-44b Hubble Wide Field Image
Text link to the HST press release describing this image

MAIN SEQUENCE STARS

Main sequence stars are stars, like our Sun, that fuse hydrogen atoms together to make helium atoms in their cores. For a given chemical composition and stellar age, a stars' luminosity, the total energy radiated by the star per unit time, depends only on its mass. Stars that are ten times more massive than the Sun are over a thousand times more luminous than the Sun. However, we should not be too embarrassed by the Sun's low luminosity: it is ten times brighter than a star half its mass. The more massive a main sequence star, the brighter and bluer it is. For example, Sirius, the dog star, located to the lower left of the constellation Orion, is more massive than the Sun, and is noticeably bluer. On the other hand, Proxima Centauri, our nearest neighbor, is less massive than the Sun, and is thus redder and less luminous.

Since stars have a limited supply of hydrogen in their cores, they have a limited lifetime as main sequence stars. This lifetime is proportional to $f\,M\,/\,L$, where f is the fraction of the total mass of the star, M, available for nuclear burning in the core and L is the average luminosity of the star during its main sequence lifetime. Because of the strong dependence of luminosity on mass, stellar lifetimes depend sensitively on mass. Thus, it is fortunate that our Sun is not more massive than it is since high mass stars rapidly exhaust their core hydrogen supply. Once a star exhausts its core hydrogen supply, the star becomes redder, larger, and more luminous: it becomes a red giant star. This relationship between mass and lifetime enables astronomers to put a lower limit on the age of the universe.

DEATH OF AN "ORDINARY" STAR

After a low mass star like the Sun exhausts the supply of hydrogen in its core, there is no longer any source of heat to support the core against gravity. Hydrogen burning continues in a shell around the core and the star evolves into a red giant. When the Sun becomes a red giant, its atmosphere will envelope the Earth and our planet will be consumed in a fiery death.

Meanwhile, the core of the star collapses under gravity's pull until it reaches a high enough density to start burning helium to carbon. The helium burning phase will last about 100 million years, until the helium is exhausted in the core and the star

becomes a red supergiant. At this stage, the Sun will have an outer envelope extending out towards Jupiter. During this brief phase of its existence, which lasts only a few tens of thousands of years, the Sun will lose mass in a powerful wind. Eventually, the Sun will lose all of the mass in its envelope and leave behind a hot core of carbon embedded in a nebula of expelled gas. Radiation from this hot core will ionize the nebula, producing a striking "planetary nebula", much like the nebulae seen around the remnants of other stars. The carbon core will eventually cool and become a white dwarf, the dense dim remnant of a once bright star.

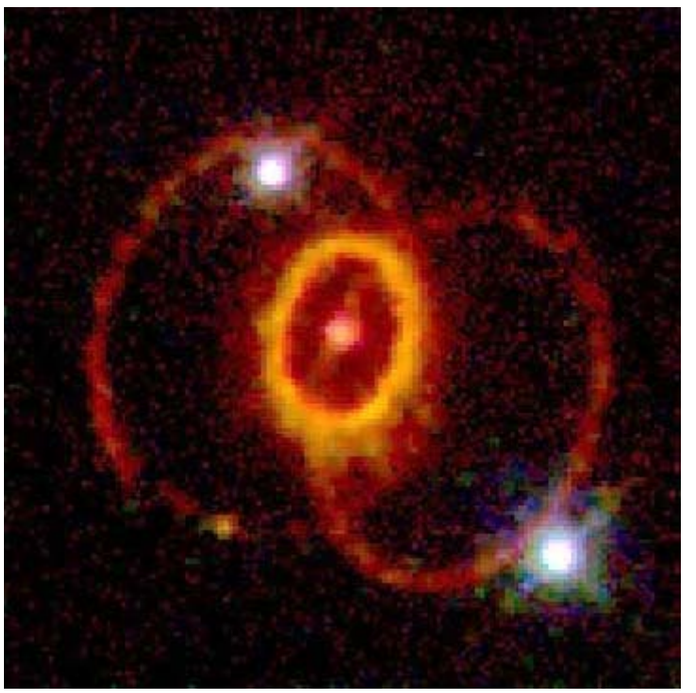
Image of a Planetary Nebula:

NGC 6543 Hubble Wide Field Image
Text Link to the HST press release describing this image

DEATH OF A MASSIVE STAR

Massive stars burn brighter and perish more dramatically than most. When a star ten times more massive than Sun exhaust the helium in the core, the nuclear burning cycle continues. The carbon core contracts further and reaches high enough temperature to burn carbon to oxygen, neon, silicon, sulfur and finally to iron. Iron is the most stable form of nuclear matter and there is no energy to be gained by burning it to any heavier element. Without any source of heat to balance the gravity, the iron core collapses until it reaches nuclear densities. This high density core resists further collapse causing the infalling matter to "bounce" off the core. This sudden core bounce (which includes the release of energetic neutrinos from the core) produces a supernova explosion. For one brilliant month, a single star burns brighter than a whole galaxy of a billion stars. Supernova explosions inject carbon, oxygen, silicon and other heavy elements up to iron into interstellar space. They are also the site where most of the elements heavier than iron are produced. This heavy element enriched gas will be incorporated into future generations of stars and planets. Without supernova, the fiery death of massive stars, there would be no carbon, oxygen or other elements that make life possible.

Image of a Supernova Remnant:



Supernova 1987A Hubble Wide Field Image
Text Link to the HST press release describing this image

The fate of the hot neutron core depends upon the mass of the progenitor star. If the progenitor mass is around ten times the mass of the Sun, the neutron star core will cool to form a neutron star. Neutron stars are potentially detectable as "pulsars", powerful beacons of radio emission. If the progenitor mass is larger, then the resultant core is so heavy that not even nuclear forces can resist the pull of gravity and the core collapses to form a black hole.

Learn more about the late stages of stellar evolution from the Chandra mission's web pages:

- White Dwarfs
- Neutron Stars
- Black Holes
- Supernovae

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

Glossary of Technical Terms

Angular resolution
The smallest angular size that the instrument can resolve.

Anisotropy
The difference in the property of a system with changes in direction. In this case, anisotropy refers to the difference in the temperature of the cosmic microwave background radiation with direction.

Antenna temperature
Antenna temperature is a way of expressing the brightness of a radiation source - it is proportional to the power per unit area emitted by the source. In most cases where it is used it corresponds to the thermodynamic or physical temperature of the source being observed. It thus relates the power emitted by the source to an interesting physical property of that source.

When we observe the brightness of the CMB, we often express the measurements in units of antenna temperature for the same reason. However, because the CMB is so cold, 2.75 K (degrees above absolute zero), the correspondence between antenna temperature and physical temperature breaks down above ~70 GHz in frequency, as shown for example in this plot.

Cosmological Constant
Einstein first proposed the cosmological constant (not to be confused with the Hubble Constant), usually symbolized by the greek letter "lambda" (Λ), as a mathematical fix to the theory of general relativity. In its simplest form, general relativity predicted that the universe must either expand or contract. Einstein thought the universe was static, so he added this new term to stop the expansion. When Hubble's study of nearby galaxies showed that the universe was in fact expanding, Einstein regretted modifying his elegant theory and viewed the cosmological constant term as his "greatest mistake".

Many cosmologists advocate reviving the cosmological constant term on theoretical grounds, as a way to explain the rate of expansion of the universe. Modern field theory now associates this term with the energy density of the vacuum. For this energy density to be comparable to other forms of matter in the universe, it would require new physics theories. So the addition of a cosmological constant term has profound implications for particle physics and our understanding of the fundamental forces of nature.

Energy Spectrum
The amount of energy emitted at a specific wavelength of light. For example, the Sun emits light at many wavelengths, which can be seen by passing sunlight through a prism. The energy spectrum of sunlight is strongest at the wavelength of yellow light, thus the Sun appears yellow to our eyes.

Feed
A component that "feeds" the signal from the optical system to the amplification electronics. Also called a "feed horn" or "horn".

HEMT
High Electron Mobility Transistor. This is a particular kind of transistor that is especially appropriate for use in microwave amplifiers.

Horizon
The limiting distance from which we can have received information since the Big Bang, 13.7 billion years ago, due to the finite speed of light. Since the universe has been expanding throughout its history, the "proper" distance to our horizon today is close to 45 billion light-years. This bounds our observable universe.

Ionized
The state in which an atom is missing one or more of its electrons, and is therefore positively charged. An ionized gas is one in which some or all of the atoms are ionized, rather than electrically neutral. The ionized electrons behave as free particles in this gas.

Isotope
Atoms which have the same number of protons in the nucleus (this defines an element), but a different number of neutrons. This changes the atomic mass, producing a "variety" of the element.

Kelvin
One Kelvin degree is equivalent to one Celsius degree. The difference between the two temperature scales: All motion within an atom ceases at zero Kelvin (K) -- this point is called absolute zero. Water freezes at zero degrees Celsius, which is approximately 273.16K.

Lagrange Points
Positions in space where the gravitational pull of the two large masses precisely equals the centripetal force required to rotate with them.

Last Scattering Surface
Also known as the Surface of Last Scattering. This is the point at which the ionized plasma that filled the early universe cooled to less than 2967 kelvin. At this temperature electrons and protons were then able to combined to make neutral hydrogen, allowing photons to travel through space without scattering. While this happened everywhere at the same time, our vantage point on Earth, 13.7 million years later, results in the view of a surrounding bubble of faint microwave light to reach us from that long ago time.

MIDEX
NASA's Mid-Class Explorer.

Sensitivity
The level of random noise in the temperature measurement.

Structure
The patterns of the distribution of matter in the universe, as probed by the cosmic microwave background radiation or observations of galaxies.

Systematic Errors
Measurement errors that are not random.

Theory
A scientifically testable general principle or body of principles offered to explain observed phenomena. In scientific usage, a theory is distinct from a hypothesis (or conjecture) that is proposed to explain previously observed phenomena. For a hypothesis to rise to the level of theory, it must predict the existence of new phenomena that are subsequently observed. A theory can be overturned if new phenomena are observed that directly contradict the theory.

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010

Wilkinson Microwave Anisotropy Probe

Suggested Reading

POPULAR COSMOLOGY (BOOKS):

- A Brief History of Time
  by Stephen Hawking
- Quarks, Leptons and the Big Bang
  by Jonathan Allday
- The Accelerating Universe : Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos
  by Mario Livio (Foreword by Allan Sandage)
- One Universe: At Home in the Cosmos
  by Neil De Grasse Tyson, et al
- The Inflationary Universe: The Quest for a New Theory of Cosmic Origins
  by Alan H. Guth (Foreword by Alan P. Lightman)
- Quintessence: The Mystery of the Missing Mass in the Universe
  by Lawrence M. Krauss
- The First Three Minutes: A Modern View of the Origin of the Universe
  by Steven Weinberg
- Measuring the Universe: Our Historic Quest to Chart the Horizons of Space and Time
  by Kitty Ferguson
- Echo of the Big Bang *(discusses the WMAP Mission)*
  by Michael D. Lemonick
- Just Six Numbers : The Deep Forces that Shape the Universe
  by Martin J. Rees
- How the Universe Got Its Spots: Diary of a Finite Time in a Finite Space
  by Janna Levin
- The Five Ages of the Universe : Inside the Physics of Eternity
  by Fred Adams, Greg Laughlin
- Before the Beginning : Our Universe and Others (Helix Books)
  by Martin J. Rees
- In Search of the Edge of Time : Black Holes, White Holes, Wormholes
  by John Gribbin
- The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos
  by Robert P. Kirshner
- The Sky Is Not The Limit : Adventures of an Urban Astrophysicist
  by Neil De Grasse Tyson
- The Little Book of the Big Bang : A Cosmic Primer
  by Craig J. Hogan (Foreword by Martin Rees)
- Astrophysical Concepts (Astronomy and Astrophysics Library)
  by Martin Harwit
- The Very First Light : The True Inside Story of the Scientific Journey Back to the Dawn of the Universe
  by John C. Mather, John Boslough
- Afterglow of Creation : From the Fireball to the Discovery of Cosmic Ripples
  by Marcus Chown
- The Elegant Universe : Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory
  by Brian Greene
- After the First Three Minutes : The Story of Our Universe
  by T. Padmanabhan
- The Whole Shebang : A State-Of-The-Universe(s) Report
  by Timothy Ferris
- Astronomy For Dummies
  by Stephen Maran
- The Origin of the Universe (Science Masters Series)

by John D. Barrow

- The Big Bang
  by Joseph Silk
- Black Holes and Time Warps: Einstein's Outrageous Legacy
  by Kip S. Thorne
- Three Roads to Quantum Gravity
  by Lee Smolin

POPULAR COSMOLOGY (MAGAZINES):

- Decoding the oldest Light in the Universe; Sky & Telescope, May 2008; 18-23 pp.
  by by Gary Hinshaw and Robert Naeye
- Misconceptions about the Big Bang; Scientific American, March 2005; 10 pp.
  by by Charles H. Lineweaver and Tamara M. Davis

ADVANCED READING:

- 3K : The Cosmic Microwave Background Radiation
  by R. B. Partridge
- Principles of Physical Cosmology
  by Phillip J. E. Peebles
- Cosmological Physics
  by John A. Peacock

wmap.gsfc.nasa.gov
Webmaster: Britt Griswold
NASA Official: Dr. Edward J. Wollack
Page Updated: Friday, 04-16-2010